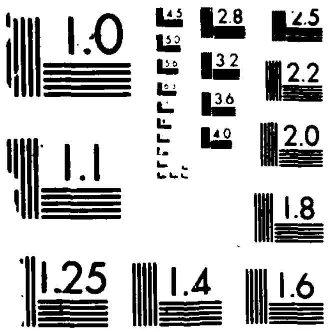
AD-A182 867 JOINT SERVICES ELECTRONICS PROGRAM(U) ILLINOIS UNIV AT URBANA COORDINATED SCIENCE LAB W K JENKINS 31 MAR 87 N00014-84-C-0149 1/1

UNCLASSIFIED F/G 9/1 NL



MICROCOPY RESOLUTION TEST CHART

COORDINATED SCIENCE LABORATORY

PROGRESS REPORT FOR THE JOINT SERVICES ELECTRONICS PROGRAM

FOR THE PERIOD
APRIL 1, 1986, THROUGH MARCH 31, 1987
FOR
CONTRACT N00014-84-C-0149

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

5

OFFICE OF NAVAL RESEARCH

PROGRESS REPORT

For the Period

1 April 1986 through 31 March 1987

for

Contract N00014-84-C-0149

Title of Contract
Joint Services Electronics Program

Name of Principal Investigator
William Kenneth Jenkins
Coordinated Science Laboratory

Name of Organization
THE BOARD OF TRUSTEES OF THE UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
Grants and Contracts Office

Address of Organization
506 S. Wright Street
Urbana, IL 61801

TABLE OF CONTENTS

RESEARCH AREA: Electromagnetics

RESEARCH AREA: Information Systems

RESEARCH AREA: Electronics Research

EXECUTIVE SUMMARY

I. Summary of the Program

This report summarizes the research that was carried out under the Joint Services Electronics Program at the University of Illinois at Urbana-Champaign during the period April 1, 1986, through March 31, 1987. Since the new 3-year JSEP contract began on October 1, 1986, this reporting period covers the last six months of the previous JSEP contract, as well as the first six months of the present one. The JSEP contract that began on October 1, 1986, contains 22 work units (Unit 3 of the new contract was not funded), which is a reduction from the 26 work units in the previous contract. Two previously supported units in the surface physics area were dropped: (1) the unit on acoustic charge transport (Professor Hunsinger) is now funded by DARPA, and (2) Professor Davidson has become Associate Director of the Center for Supercomputer Research and Development. His work on computer architecture is now funded by DOE, NSF, and private industry. The old unit (Unit 3) on vapor phase growth and characterization was replaced by the new Unit 5 on MOCVD-grown heterostructure electronic devices under the direction of Professor J. J. Coleman. In the new contract, Professor Thornton has been added to investigate chemistry processes in plasma discharges (Unit 9), and Professor Lyding, a new recruit, was added to Unit 8 (formerly Unit 10) to perform some key experiments supporting the charge density wave theory work under the direction of Professor Tucker. The previous unit on hierarchical design aids was replaced by the new Unit 7 on high-performance integrated circuits. Two new faculty, Professors Kang and Rao, have replaced Professor Trick, who has become the new Head of Electrical and Computer Engineering and another faculty member who is no longer with the university (Professor Mayeda).

In the electromagnetics area, Professors Chuang and Lo are new to the unit on monolithic millimeter wave ICs (Unit 11). Professor Chuang is a new faculty member from MIT with a unique background in both semiconductors and electromagnetics. In the new contract, Unit 12 on inverse scattering under the direction of Professor Mittra was expanded due to increased interest in this subject.

In the information systems area, three new faculty were recruited in fault-tolerant computing (Professors Fuchs, Banerjee, and Iyer), and a new Unit 17 on parallel VLSI structures for sensor array processing has been added with two new faculty, Professors Arun and Wah. Finally, a total of six new faculty in the areas of adaptive and nonlinear systems, communication systems, and statistical signal processing were added at the beginning of the new contract in October 1986 (Professors Kumar, Medanic, Grizzle, Poolla, Arikan, and Barron).

Professor Jenkins has served as Acting Director of the Coordinated Science Laboratory during the last academic year to replace Professor Trick, and both Jenkins and Trick have been sharing the responsibilities of JSEP principal investigator since August 1, 1986. Recently, Professor Jenkins has been named as the new Director of CSL and will assume the position on a permanent basis on May 21, 1987.

II. Most Outstanding Accomplishments

There are three particular items that we would like to cite as the most significant accomplishments on the JSEP Program during this reporting period, each of which is described briefly below. These are the development of a new heterostructure hot electron diode, new error-control coding and spread-spectrum communication results that have been incorporated into the Army's SINCGARS radio, and the successful design and fabrication of a VLSI integrated circuit that contains a programmable digital filter module whose design is based on modern residue number arithmetic techniques.

The Heterostructure Hot Electron Diode

Professors J. J. Coleman and K. Hess, together with graduate students T. K. Higman and M. A. Emanuel have discovered a new switching mechanism in semiconductor heterostructures which has resulted in the development of a new electronic device, the heterostructure hot electron diode (H^2ED). The operation of the H^2ED is based on a transition between two current conduction modes in a two-terminal structure, a low current tunneling mode, and a high current thermionic emission mode. Switching between these modes gives rise to an S-shaped negative differential resistance in the current versus voltage characteristic. These devices have application as a microwave oscillator. Microwave characterization is presently in progress, and preliminary results have demonstrated test-fixture-limited gain to 18 GHz. If no parasitic effects are encountered, and if the oscillation frequency is, in fact, electron transit time limited, oscillation in the 1000 GHz range may be possible.

This work represents a synergistic relationship between Professor Hess' theoretical work supported under Unit 2 and Professor Coleman's experimental work supported under Unit 5. Professor Hess developed the theoretical model of the new device and predicted its characteristics. Professor Coleman built the new device in his laboratory, measured the physical characteristics of his experimental sample, and is presently continuing its further characterization and development. It was announced in a press release by the University of Illinois at Urbana-Champaign to the UPI wire service that a patent disclosure has been filed on this new device, and a number of publications have either appeared or will be forthcoming soon describing the technical details of the H^2ED (see Unit 5, Research Summary).

Error-Control Coding and Spread-Spectrum Communication Techniques for the Army's SINCGARS Radio

Several results of CSL research in error-control coding and spread-spectrum communications have recently been incorporated into the SINCGARS radio (Single Channel Ground/Airborne Radio Subsystem). This radio, the Army's newest tactical radio, was developed by ITT Aerospace/Optical Division for voice and data communications. It operates in both a single-channel mode and a frequency-hop spread-spectrum mode. In addition, an overlay is being developed by ITT and SRI International to enable SINCGARS radios to operate as packet radios in a mobile communication network.

Research results obtained by CSL Professors M. B. Pursley and D. V. Sarwate and their graduate research assistants were employed by Professor Pursley to design the synchronization sequence that is utilized for timing acquisition in the SINCGARS receiver. In addition, for the packet radio version of SINCGARS (known as the SINCGARS Packet Overlay), Professor Pursley developed the error-control method which combines Reed-Solomon codes with side information derived from test patterns. The side information is used to erase unreliable data at the output of the demodulator so that the input to the decoder is a combination of data symbols and special erasure symbols. The code enables the receiver to correct errors and erasures caused by noise and interference in the communication channel. The combination of coding and side information provides the capability for a large number of SINCGARS radios to operate simultaneously in the same frequency band, and it also improves the radio's ability to communicate in the presence of various types of electromagnetic interference.

The decoding algorithm, which was developed and implemented in software by Professor Sarwate, is basically a mathematical description of the computations that are required to correct both errors and erasures. The actual computations prescribed by the algorithm are carried out in a microprocessor contained in the radio. The resulting decoder is capable of handling data rates in excess of 16,000 data symbols per second, the maximum signaling rate of the SINCGARS radio.

Professor Pursley also provided the analytical tools to evaluate the performance of the error-control scheme and assess its impact on the overall communication network performance. Analytical results from this effort, and other investigations conducted by Professor Pursley and Mr. J. R. McChesney of ITT, were used subsequently in the SINCGARS packet radio network simulation developed for the Army by SRI.

The research leading to the development of the approach used for error control in the SINCGARS radio was funded by JSEP during the early stages, funded by ARO during later stages, and developed into the actual SINCGARS application under UI contracts with ITT and individual consulting arrangements with SRI and ITT.

Design and Fabrication of a VLSI Digital Filter Module

For a number of years both NSF and JSEP have supported theoretic studies at the Coordinated Science Laboratory on the use of residue number arithmetic (RNS) for the design of high-speed VLSI circuits for the digital signal processing functions that are required in modern communication and radar systems. During the last year, Professors Jenkins, Arun, and Wah have carried out the successful design and fabrication of a semicustom VLSI digital filter module which demonstrates both the feasibility and desirability of using residue number theory design techniques in practice (Unit 17). A semicustom integrated circuit module was designed for an RNS digital filter using the IBM MVISA CAD system that is located on the campus of the University of Illinois at Urbana-Champaign. A programmable 4-bit module was designed as a basic building block for a finite impulse response digital filter that has order 8 and 14 bits of arithmetic precision. The module was designed using finite field logarithm additions to completely eliminate conventional multipliers on the chip and thereby improve speed and circuit density. The chip design was done with MVISA using a standard cell approach, and MVISA was then used to simulate the hardware operation and to estimate physical parameters. The chip was subsequently fabricated at the IBM Manassas facility, and 10 samples were recently returned to the University of Illinois at Urbana-Champaign for testing and characterization. MVISA estimates that the 4.2 mm chip consumes 89 mW and operates at a system cycle frequency of 10 mHZ, which corresponds to a data-cycle frequency of 1.2 mHz. The design used 529 out of a possible 560 available standard cells. Correct operation of the circuits has not yet been verified since they were received only two weeks ago. However, since the circuits were designed with testability in mind, and due to the modular nature of the RNS architecture, it is believed that testing will be a straightforward matter.

The development of this VLSI digital filter module would not have been possible without the theoretical support that was provided by NSF, VHSIC, and JSEP for many years, the synergistic research interaction between the Computer Systems Group (Units 13 and 14) and the Digital Signal and Image Processing Group (Units 16 and 17), and the support of private industry (IBM) who served as a silicon foundry for chip fabrication. This work was recently presented at the 1987 International Symposium on Circuits and Systems and will be described in further detail in several forthcoming publications (see Unit 17). It is expected that the interdisciplinary team effort that was put together for this project will serve as a model for future research projects of this type.

WORK UNIT NUMBER 1

TITLE: Crystal Growth from the Vapor Phase and Controlled Doping of Equilibrium and Metastable Semiconductor Alloys: Ion-Surface Interactions

SENIOR PRINCIPAL INVESTIGATORS:

J.E. Greene, Research Professor
S.I. Shah, Research Associate

SCIENTIFIC PERSONNEL AND TITLES:

P. Fons, Research Assistant
S. Gorbatkin, Research Assistant
B. Kramer, Research Assistant
D. Lubben, Research Assistant
D. McIntyre, Research Assistant
D. Mei, Research Assistant
M.A. Ray, Research Assistant
A. Rockett, Research Assistant
L. Romano, Research Assistant

SCIENTIFIC OBJECTIVE:

The primary objective of this research program is to investigate energetic particle-surface interactions which control the nucleation and growth kinetics, chemistry, and physical properties of alloy semiconductors during vapor phase crystal growth by UHV ion beam sputtering and accelerated-beam molecular beam epitaxy. In both of these growth techniques, low energy ion-surface interactions allow an efficient coupling of kinetic energy to the growth surface upon condensation, thereby altering the surface reactivity as well as adsorption and adatom diffusion kinetics allowing single crystal film growth at lower temperatures, much more precise control over dopant incorporation probabilities and depth distributions, and the growth of unique metastable alloys. This work is being pursued from both an analytical and an experimental point of view in order to establish a detailed understanding of the fundamental film growth mechanisms.

SUMMARY OF RESEARCH:

Surface Reaction Mechanisms, Elemental Incorporation Probabilities, and Depth Distributions of Accelerated and Thermal Dopants in Semiconductor Films Grown from the Vapor Phase

As reported last year, we have developed a general time-dependent model, which combines thermodynamic and kinetic elements, for describing the incorporation of dopants into films during deposition. The model accounts for dopant surface segregation and allows elemental incorporation probabilities σ and depth-dependent concentration profiles $C(x,t)$ to be calculated as a function of experimental parameters such as film and dopant material, deposition rate, incident dopant flux, growth temperature, etc.

Calculated profiles from arbitrarily complex doping schedules for both thermal and accelerated dopants are in excellent agreement with experimental results for a variety of dopants in MBE Si, MBE and sputter-deposited GaAs, and MBE $Ga_{1-x}Al_xAs$. Moreover, we have used the model to predict critical temperatures for transitions in dopant segregation regimes, dopant-induced surface structural phase transitions, and changes in dopant/surface reaction paths leading to large modifications in surface binding energies and hence incorporation probabilities. All of these effects have now been observed experimentally. Additional terms have been added to the model to account for trapping (i.e. low-energy implantation) and enhanced segregation associated with the use of accelerated dopants. The extended model has been shown to work very well for acceleration energies of a few hundred eV or more where low-energy implantation is the dominate effect.

Selected results from our experimental investigations are briefly summarized below.

- The Si incorporation probability σ_{Si} and segregation-induced profile broadening δ_{Si} of nominally abrupt Si doping modulations during the growth of MBE $Ga_{1-x}Al_xAs$ have been determined as a function of T_s, x, and As_2 overpressure P_{As} during growth. Si segregation in $Ga_{1-x}Al_xAs$, while quite small compared to other dopants such as Sn, was (contrary to popular belief) measurable. δ_{Si} ranged form ~ 7 nm at 600°C to 25 nm at 725°C and segregation was kinetically limited over this T_s range. δ_{Si} increased slightly with x, but varying P_{As} by a factor of three had no measurable effect. A lower limit for the Gibbs free energy of segregation was found to be 0.4 eV. σ_{Si} varied from 1 at $T_s \leqslant 600$°C to ~ 0.5 at 725°C and was not a strong function of either x or P_{As}. The surface binding energy of Si was estimated to be 3 ± 0.1 eV.

- The incorporation probability of thermal In, a deep acceptor, in MBE Si(100) was undetectable at normal growth temperatures and was of the order of 10^{-5} at $T_s = 475$°C. This low incorporation probability results from the combined effects of a strong tendency for In atoms to follow the advancing Si film surface and the relatively high desorption rate of In at Si growth temperatures. The steady-state In surface coverage θ_{In} on the growing Si surface accumulates to cause the surface reconstruction to change from the initial Si(2x1) to In-stabilized (3x4), corresponding to $\theta_{In} > 0.1$ monolayer (ML), and then to In(3x4) with Si(310) facets at $\theta_{In} > 0.7$ ML **without** any detectable In incorporation in the Si film.

Using a single-grid, UHV compatible ion source of our own design to provide accelerated In^+ doping beams, we have obtained σ_{In} values of 0.02-0.7 in Si(100) films grown at 800°C with In^+ acceleration energies E_{In} between 50 and 400 eV. Combined SIMS and T-dependent Hall and resistivity measurements carried out on films grown with $E_{In} = 200$ eV showed that In was incorporated substitutionally into electrically-active sites over the entire concentration range examined, $10^{16}-10^{19}\ cm^{-3}$ (well above equilibrium solid-solubility limits!). The acceptor level ionization energy was 165 meV, in agreement with bulk Si results, and there was no evidence for the 111 meV level associated with In-C complexes that is reported for annealed In-implanted Si. Carrier mobilities were higher than the best results reported for In-implanted Si and above Irvin-curve values for bulk Si. There was no evidence for residual lattice damage in the films until E_{In} was increased to 500 eV while T_s was decreased to 600°C where incomplete In substitutionality and a loss of ~ 30% in mobility were observed.

- We previously determined and modeled the detailed mechanism and the kinetics of the dissociative chemisorption of Sb_4 on Si(100)2x1 surfaces (see earlier reports and Barnett, Winters, and Greene, *Surf. Sci. 165*, 303 (1986)) and calculated thermal Sb incorporation behavior in MBE Si (see Barnett and Greene, *Surf. Sci. 151*, 67 (1985)). We have recently begun experiments with a new ion gun to investigate the incorporation of low-energy accelerated Sb^+ ions during MBE Si.

Low-Energy Ion/Surface Interactions During Crystal Growth

Low-energy ion-irradiation of the film *during* deposition can be used to provide an efficient coupling of kinetic energy to the growth surface in order to alter surface reactivity as well as adsorption, adatom diffusion, nucleation, and growth kinetics. Such effects have been reported by laboratories across the world using a variety of film growth techniques including accelerated-beam MBE, Pa-CVD, and sputter deposition (see Greene, *Solid State Technology* April, 1987 for a recent review). This in turn can lead to lower epitaxial temperatures, more control over elemental incorporation probabilities, and the growth of unique metastable alloys. Our group has been modeling ion/surface interaction effects which are common to all of these techniques and have carried out the first definitive experiments under well-controlled conditions to probe fundamental mechanisms. Some highlights are described briefly below.

- We, and others, have predicted that one of the important roles of low-energy ion irradiation during the initial stages of film nucleation is to provide preferred adsorption sites (i.e. non-random nucleation sites). We have recently developed experimental techniques using thermally stimulated desorption (TSD) and modulated-beam mass spectrometry (MBMS) to actually measure such effects for the first time. Si(100)2x1 surfaces at T_s = 425°C were irradiated in separate experiments, during and after deposition of 1 ML of Sb. In both cases, in addition to the normal thermal Sb binding energy site at 2.33 eV (which we had reported previously), we observed an additional higher binding energy site at 2.6 eV. The Sb coverage in the E_2 site increased with ion dose and a model was developed that provided a good fit to the data and allowed us to calculate Sb trapping probabilities.

- We have, for the first time, investigated the nucleation and growth of films deposited from accelerated beams under well controlled conditions in UHV. Transmission electron microscopy was used to directly observe the kinetics of film growth from partially ionized In beams on electron-transparent Si_3N_4 windows. The use of acceleration energies ranging from 0 to 300 eV were found to dramatically alter nucleation kinetics leading to a progressive shift toward larger average island diameters with a more uniform size distribution. Secondary island formation was almost entirely suppressed due primarily to ion-irradiation-induced dissociation of small clusters and enhanced adatom diffusion. However, we believe that the mechanism for enhanced adatom diffusion is quite different than the one that is popularly held.

Crystal Growth and Physical Properties of Single-Crystal Metastable Semiconductors

We have carried out the first detailed studies of the growth and physical properties of new single-crystal metastable semiconductors. The key feature stabilizing the growth of these material is the controlled use of low-energy ion bombardment to modify the incorporation probabilities of the matrix elements and to promote dynamic collisional mixing during deposition.

- Single-phase metastable $Ge_{1-x}Sn_x$ alloys with a diamond-cubic structure have been grown with Sn concentrations up to 15 at % (the maximum equilibrium solid solubility is ~ 1 at %). Films with x ≤ 0.08 grown on Ge(100) and GaAs(100) substrates were single crystals while films grown on amorphous glass were polycrystalline with a (220) preferred orientation. The allowable range in obtaining single-phase crystalline alloys was a function of x (the thermodynamic driving force for phase separation increases with increasing Sn concentration) and the ion flux and acceleration energy. A growth phase map plotted as a function of x, T_s, and E was determined. Raman spectra of $Ge_{1-x}Sn_x$ alloys exhibit a two peak density of states which can be explained by assuming the Sn substitution introduces disorder in the bonding direction and removes the degeneracy of the optical branches.

- $GaAs_{1-x}Sb_x$ alloys, of interest for fabrication of sources and detectors in the ≥ 1 μm range for fiber-optics communications, have been grown on GaAs(100) substrates at compositions across the entire pseudobinary range. Under equilibrium conditions, the alloy system exhibits a miscibility gap from x ~ 0.2 to 0.9 at the growth temperature. X-ray diffraction, optical absorption, and Raman spectra showed that our samples were single-crystal, single-phase, alloys for all x. Alloy lattice constants varied linearly with concentration while the direct Γ-point optical bandgap showed significant bowing with a minimum near x = 0.8. Raman spectra exhibited a two-mode behavior throughout the alloy system including a local mode of As in GaSb and a resonant mode of Sb in GaAs. This is contrary to previous reports of a "one-two" mode behavior in OMCVD $GaAs_{1-x}Sb_x$ for which spinoidal decomposition was suspected. Moreover, the Raman peaks from our films had peak broadenings and assymmetries much less than these observed in the OMCVD samples and, in fact, less than those of MBE $Ga_{1-x}Al_xAs$.

JSEP-SPONSORED PUBLICATIONS

[1] S. A. Barnett, H. F. Winters, and J. E. Greene, "The interaction of Sb_4 molecular beams with Si(100) surfaces: Modulated-beam mass spectrometry and thermally stimulated desorption studies," *Surf. Sci.*, vol. 165, p. 303, 1986. (JSEP/SRC)

[2] J. Knall, J.-E. Sundgren, G. V. Hansson, and J. E. Greene, "In overlayers on clean Si(100)2x1: Surface structure, nucleation, and growth," *Surf. Sci.*, vol. 166, p. 512, 1986. (JSEP/SRC)

[3] A. Rockett, J. Knall, M. A. Hassan, J.-E. Sundgren, S. A. Barnett, and J. E. Greeene, "Thermal and accelerated ($\leqslant$ 200 eV) In doping of Si(100) layers during molecular beam epitaxy," *J. Vac. Sci. Technol. A*, vol. 4, p. 900, 1986. (JSEP/SRC)

[4] A. Rockett, J. Klem, S. A. Barnett, J. E. Greene, and H. Morkoc, "Si incorporation and segregation on $Ga_{1-x}Al_xAs$ (100) films grown by molecular beam epitaxy," *J. Vac. Sci. Technol. B*, vol. 4, p. 519, 1986. (JSEP)

[5] A. Rockett, J. Klem, S. A. Barnett, J. E. Greene, and H. Morkoc, "Si incorporation probabilities and depth distributions in $Ga_{1-x}Al_xAs$ films growtn by molecular beam epitaxy," *J. Appl. Phys.*, vol. 59, p. 2777, 1986. (JSEP)

[6] T. C. McGlinn, T. N. Krabach, M. V. Klein, G. Bajor, J. E. Greene, B. Kramer, S. A. Barnett, A. Lastras, and S. Gorbatkin, "Raman scattering and optical absorption studies of the metastable alloy system $GaAs_{1-x}Sb_x$," *Phys. Rev. B*, vol. 33, p. 8396, 1986. (JSEP)

[7] J. E. Greene, T. Motooka, J.-E. Sundgren, A. Rockett, S. Gorbatkin, D. Lubben, and S. A. Barnett, "A review of the present understanding of the role of ion/surface interactions and photo-induced reactions during vapor phase crystal growth," *J. Cryst. Growth*, vol. 79, p. 19, 1986. (JSEP/DOE/SRC)

[8] M. A. Hasan, J. Knall, S. A. Barnett, J.-E. Sundgren, A. Rockett and J. E. Greene, "Accelerated-ion beam doping during Si growth by molecular beam epitaxy and Ion-enhanced In film deposition using low energy (40 to 300 eV) In^+ Ion source," *Vacuum*, in press. (JSEP/SRC)

[9] S. A. Barnett, H. F. Winters, and J. E. Greene, "Influence of Ion bombardment on the interaction of Sb with the Si(100) surface," *Surf. Sci.*, in press. (JSEP/SRC)

[10] S. I. Shah, J. E. Greene, L. L. Abels, Q. Yao, and P. M. Raccah, "Growth of single-crystal metastable $Ge_{1-x}Sn_x$ alloys on Ge(100) and GaAs(100)) substrates," *J. Crystal Growth*, in press. (JSEP/DOE)

[11] J. E. Greene, "Crystal growth, atomic ordering, and physical properties of epitaxial metastable semiconductors," *J. Vac. Sci. Technol.*, in press. (JSEP/DOE)

[12] J. E. Greene, T. Motooka, J.-E. Sundgren, D. Lubben, S. Gorbatkin, and S. A. Barnett, "The role of Ion/surface interactions and photo-induced reactions during film growth from the vapor phase," *J. Nucl. Instr. Methods B*, in press. (JSEP/DOE/SRC)

[13] J. E. Greene, "Low-energy Ion bombardment during film deposition from the vapor phase: Effects on microchemistry and microstructure," *Sol. St. Technol.*, in press. (JSEP/SRC/DOE)

[14] D. H. Rich, A. Samsavar, T. Miller, H. F. Lin, T.-C. Chiang, J.-E. Sundgren, and J. E. Greene, "Coordination determination of In on Si(100) from synchrotron photoemission studies," *Phys. Rev. Lett.*, in press. (JSEP SRC)

[15] M.-A. Hasan, S. A. Barnett, J.-E. Sundgren, and J. E. Greene, "Nucleation and initial growth of In deposited on Si_3N_4 using low-energy ($\leqslant$ 300 eV) accelerated beams in ultra-high Vacuum," *J. Vac. Sci. Technol.*, in press. (JSEP SRC)

WORK UNIT NUMBER 2

TITLE: Studies of Transport Phenomena in Semiconductors

SENIOR PRINCIPAL INVESTIGATORS:

K. Hess, Research Professor
J. P. Leburton, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

D. Bailey, Research Assistant
J. Higman, Research Assistant
S. Manion, Research Assistant

SCIENTIFIC OBJECTIVE:

This research involves the study of basic properties of semiconductors, semiconductor-heterolayers, new device concepts and device simulation. Both theoretical and experimental methods are employed in each of these categories. We are examining a variety of hot electron phenomena and their effects on present and future device performance, especially in connection with modulation doping. The experiment studies concern mainly electronic transport in heterolayers in high electric and high magnetic fields.

The theoretical studies include Monte Carlo simulations of electronic transport and the development of two-dimensional models.

SUMMARY OF RESEARCH:

Novel Heterolayer Devices and Transport Effects

We have proposed a new switching mechanism in a two-terminal semiconductor heterolayer structure which capitalizes on nonlinear electron temperature effects in adjacent heterolayers [1]. We have been able to demonstrate experimentally that this mechanism can be used to fabricate oscillators with theoretical frequency limits in the Teraherz range. Oscillations have been observed up to 20 GHz limited by the experimental set up.

We have also investigated dual channel high electron mobility transistors and their ultimate switching speed by ensemble Monte Carlo simulations and have found switching speeds superior to conventional high electron mobility transistors [3,9].

Furthermore we have investigated tunneling-assisted impact ionization across the conduction-band-edge discontinuity of quantum-well heterostructures and applied the results to a new superlattice structure. We have considered multiquantum-well structures where the quantum-well regions are heavily doped and the undoped barrier regions are essentially insulating. Incident hot electrons due to the applied electric field perpendicular to the heterointerface interact with the two-dimensional electrons confined to the quantum wells through the Coulomb force. The resultant electrons can either have enough energy to get out of the wells or tunnel through the triangular barriers. A new analytical approximation for the impact ionization rate is given which compares favorably with the numerical results. The tunneling-assisted impact ionization rates and the ionization coefficients are also calculated. It is shown that the tunneling effect reduces the ionization thresholds and enhances the ionization rates significantly. This effect is a candidate for new forms of solid state devices analog to photomultipliers [6].

Electronic Transport at High Energies and Transient Phenomena:

We have continued to investigate the basic mechanisms responsible for the conductance oscillations in the "Hickmott" experiment. We have been able to complete a model based on phononization of neutral donors in the active GaAs layer of the semiconductor structure. Recent experiments using far infrared spectroscopy have demonstrated the occurrence of ionization in the oscillation cycles, which definitively excludes interpretations based on "exotic" effects such as magnetopolaron or Ihm's model. Impact ionization, as proposed by Eaves and coworkers, has been claimed to occur via a magnetic-impurity resonance (MIR) effect. We have demonstrated that the interpretation is questionable. Both phonon and impact-ionization mechanisms seem so far undistinguishable. Further experiments are necessary to identify the fundamental process causing the current oscillations. [4,5].

A second investigation (experimental) of low-temperature, high-field transport has been dealing with the energy loss rates of electrons in modulation-doped AlGaAs/GaAs heterojunctions at low temperatures. At the temperatures of this experiment, the energy loss is due to acoustic phonon scattering, mostly through the deformation potential interaction. We have developed a theory of the energy loss rate to acoustic phonons, discussed the effects of static screening, and determined a value of the deformation potential constant by matching the theory to our experimental data. We have shown how the temperature dependence of the energy loss rate can be used to determine the effectiveness of screening. In agreement with previous studies, we find that an anomalously large deformation potential constant of 16.0 or 11.5eV for the screened or unscreened theory, respectively, is necessary to explain the data [10].

INTERACTIONS AND/OR TECHNOLOGY TRANSFER:

Some of the simulation codes for transient transport have been developed in cooperation with the U. S. Army Electronics Technology and Device Laboratory, Ft. Monmouth.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] K. Hess, T. K. Higman, M. A. Emanuel, and J. J. Coleman, "New ultrafast switching mechanism in semiconductor heterostructures," *J. Appl. Phys.*, vol. 60, no. 10, pp. 3775-3777, 1986. (JSEP/ONR/ARO)

[2] J. Higman and K. Hess, "Comment on the use of the electron temperature concept for nonlinear transport problems in semiconductor p-n junctions," *Solid-State Electronics*, vol. 29, no. 9, pp. 915-918, 1986. (JSEP)

[3] I. C. Kizilyalli, K. Hess, G. J. Iafrate, and D. Smith, "Dynamics of electron transfer between two adjacent channels as calculated by an ensemble Monte Carlo method," *Proc. NUMOS Workshop*, Los Angeles, CA, Dec. 1986. (ARO/JSEP)

[4] J. P. Leburton, "Anomalous current oscillations in semiconductor-insulator-semiconductor structures and related devices," *NATO Summer School*, Antwerp, Belgium, 1986. (JSEP)

[5] J. P. Leburton, "Microscopic interpretation of the current oscillations in $GaAs^{+}$ -AlGaAs-$GaAs^{-}$ tunnel junctions," *Proc. 18th I.C.P.S.*, Stockholm, Sweden, 1986. (JSEP)

[6] S. L. Chuang and K. Hess, "Tunneling-assisted impact ionization for a superlattice," *J. Appl. Phys.* vol. 61, no. 4, Feb. 1987. (NASA/JSEP)

[7] J. P. Leburton, "Space charge generation by LO phonon ionization of neutral donors in GaAs-AlGaAs-GaAs tunnel junctions," *Bull. Am. Phys. Soc.*, vol. 32, pp. 886, 1987. (JSEP)

[8] T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, and J. J. Coleman, "Theoretical and experimental analysis of the switching mechanism in heterostructure hot electron diodes," to be published in *J. Appl. Phys.* (ARO/ONR/JSEP)

[9] I. C. Kizilyalli, K. Hess, and G. J. Iafrate, "Electron transfer between adjacent channels simulated by ensemble Monte Carlo methods," to be published in *J. Appl. Phys.* (ARO/JSEP)

[10] S. J. Manion, M. Artaki, M. A. Emanuel, J. J. Coleman, and K. Hess, "Electrons-energy-loss rates in AlGaAs/GaAs heterostructures at low temperatures," to be published in *J. Appl. Phys.* (ONR/JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] K. Yokoyama and K. Hess, "Monte Carlo study of electronic transport in $Al_{1-x}Ga_xAs/GaAs$ single-well heterostructures," *Phys. Rev.* B, vol. 33, no. 8, pp. 5595-5606, 1986. (ARO/ONR)

[12] T. Wang, K. Hess, and G. J. Iafrate, "Monte Carlo simulations of hot-electron spectroscopy in planar-doped barrier transistors," *J. Appl. Phys.*, vol. 59, no. 6, pp. 2125-2128, 1986. (ARO)

[13] K. Kim, K. Kahen, J. P. Leburton, and K. Hess, "Band-structure dependence of impact ionization rate in GaAs," *J. Appl. Phys.*, vol. 59, no. 7, pp. 2595-2596, 1986. (ONR)

[14] G. E. Stillman, V. M. Robbins, and K. Hess, "Impact ionization in InP and GaAs," *Physica*, vol. 134B, pp. 241-246, 1986. (NSF/ONR)

[15] K. Yokoyama and K. Hess, "Calculation of warm electron transport in AlGaAs/GaAs single heterostructures using a Monte Carlo method," *J. Appl. Phys.*, vol. 59, no. 11, pp. 3798-3802, June 1986. (NSF)

[16] K. Kim and K. Hess, "Simulations of electron impact ionization rate in GaAs in nonuniform electric fields," *J. Appl. Phys.*, vol. 60, no. 7, pp. 2626-2629, Oct. 1986. (ONR)

[17] K. Hess, *Large Scale Computational Device Modeling*, Proceedings of a workshop on large scale computational device modeling, Apr. 18-19, 1985, Naperville, IL, K. Hess, Editor, 1986. (NSF)

[18] P. A. Martin, K. Hess, M. Emanuel, and J. J Coleman, "Deep level transient spectroscopy studies of defects in GaAs-AlGaAs superlattices," *J Appl. Phys.*, vol. 60, no. 8, pp. 2882-2885, Oct. 1986. (ONR/ARO)

[19] I. C. Kizilyalli, K. Hess, J. L. Larson, and D. Widiger, "Scaling properties of high electron mobility transistors," *IEEE Trans. on Electron Devices*, vol. ED-33, no. 10, pp. 1427-1433, Oct. 1986. (ONR/ARO)

[20] K. B. Kahen and J. P. Leburton, "Optical constants of GaAs-AlGaAs superlattices and multiple quantum wells," *Phys. Rev.* B, vol. 33, pp. 5465-5472, 1986. (NASA)

[21] J. P. Leburton and K. B. Kahen, "Modeling of the optical properties of III-V semiconducting compounds and related heterostructures," in Proc. of 1st workshop on *Large Scale Computational Device Modeling*, K. Hess, Ed., University of Illinois, Urbana, IL 61801, 1986, pp. 119-130. (NASA)

[22] M. Wagner and J. P. Leburton, "A proposal for superstructures based high efficiency photovoltaics," *Appl. Phys. Lett.*, vol. 49, pp. 886-888, 1986. (NASA)

[23] K. B. Kahen and J. P. Leburton, "Exciton effects in the index of refraction of multiple quantum wells and superlattices," *Appl. Phys. Lett.*, vol. 49, pp. 734-736, 1986. (NASA)

[24] D. Arnold and K. Hess, "Barrier height fluctuations in very small devices due to the discreteness of the dopants," to be published in *J. Appl. Phys.* (ONR, NSF)

[25] K. Hess and G. J. Iafrate, "Modern aspects of heterojunction transport theory," to be published.

[26] K. B. Kahen and J. P. Leburton, "Index of refraction of GaAs-AlGaAs superlattices and multiple quantum wells," *Superlattices and Microstructures*, in press. (NASA)

WORK UNIT NUMBER 4

TITLE: Basic Studies of the Optical and Electronic Properties of Defects and Impurities in Compound Semiconductor Epitaxial Layers and Related Superlattices

SENIOR PRINCIPAL INVESTIGATOR:

G. E. Stillman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. S. Bose, Research Assistant
B. Lee, Research Assistant
M. H. Kim, Research Assistant
R. DeJule, Research Assistant (Sept. 1986 graduate)
M. A. Haase, Research Assistant
N. Pan, Research Assistant
A. Reed, Research Assistant
V. M. Robbins, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this research unit is to contribute to our understanding of impurity incorporation mechanisms, sources, and defects and to improve our understanding of the influence of growth conditions on impurities and defects in semiconductor materials that will be important for new multiple-layer heterostructure devices. It includes developing new characterization techniques that will extend the range of impurity concentrations over which quantitative analysis is possible.

SUMMARY OF RESEARCH:

The devices and multiple heteroepitaxial structures of interest for advanced electronic and optoelectronic applications all require the careful control of alloy composition and doping levels. Some of these devices require high-purity and low-carrier concentration layers as well, as for MODFETs, HEMTs, and quantum well avalanche photodiodes. We have developed characterization techniques (Fourier transform far-infrared photothermal ionization spectroscopy and near-infrared variable temperature photoluminescence) for identifying and quantifying the residual impurities in high-purity GaAs. These techniques are best suited to the characterization of very high-purity materials. When the residual impurity concentrations are high, as is often the case during the development of new semiconductor materials, or for small bandgap materials, it would be extremely useful to have additional techniques which are applicable to these cases. In this research, another limitation of currently available techniques is that it is not presently possible to identify donor species in p-type high-purity material. We proposed to develop high magnetic field (9T), resonantly pumped high-resolution Fourier transform magneto-photoluminescence techniques for the identification of residual donor and acceptor impurities in relatively impure n- and p-type GaAs. These techniques will also be applied to InP, AlGaAs, InGaAs, and other related alloys. This work will be critical for the development of high-purity MBE and MOCVD source materials for new compound semiconductor materials.

The Fourier Transform photoluminescence technique, with the use of very high magnetic fields, will also permit photoluminescence measurements to be extended to small bandgap materials such as InGaAs, HgCdTe, and related semiconductors. These measurements are not very effective using ordinary dispersive techniques.

During this reporting period we have achieved identification of residual donors in high-purity epitaxial GaAs by magneto-photoluminescence (MPL) measurements at a high magnetic field (9.0 T) with selective excitation. The high-purity epitaxial layers used for this identification were grown by various techniques which have characteristic residual impurities. The results of 77 K Hall effect measurements on these samples confirm the high purity of the layers. The different donor species have been detected in these layers from well-resolved "two-electron" satellites in the MPL spectra. Photothermal ionization spectroscopic (PTIS) measurements were also made on the same layers to identify the donor species present. The MPL and PTIS measurements have been correlated to identify the "two-electron" satellite peaks in the MPL spectra corresponding to the different donor species.

Magnetophotoluminescence measurements were made on the samples mounted strain free in pumped liquid helium, at a high magnetic field (9.0 T) in a superconducting solenoid in the Faraday configuration. An infrared tunable dye laser with a power of (20-30 mW) was used to pump the luminescence. Styryl 9 M dye was used to cover the range of excitation energies slightly below and above the bandgap of GaAs. The dye laser was optically pumped by ~ 2-4 watts of all lines from an argon ion laser. An arrangement of lenses was used to defocus the laser beam onto the sample. The luminescence was collected and focussed onto a four-slit 1.0 m double spectrometer and detected by a thermoelectrically cooled GaAs photomultiplier tube using the photon counting technique.

Figure 1 shows the typical PL spectrum of exciton recombination in high-purity epitaxial GaAs (sample E) grown by $AsCl_3$—VPE (vapor phase epitaxy). The spectrum was recorded at 1.7 K, low excitation intensity and a high magnetic field (9.0 T). The dye laser output was tuned close to the bandgap of GaAs. The highest energy peak labeled 'FE' is the free exciton recombination. The large peaks in the high-energy region between 1.5180 eV and 1.5193 eV are the principal lines of the donor-bound exciton (D°,X) emission. The principal lines labeled $(D^\circ,X)_{1s}$ are transitions in which the initial state is the ground state or an excited state of the (D°,X) complex, and the final state is the ground state of the donor. The peaks in the low-energy region between 1.510 eV and 1.515 eV are the "two-electron" transitions. These transitions differ in energy from the principal lines by the energy (above the donor ground state) of the final state of the transition in which the donor is left in its first excited state. At high magnetic fields, "two-electron" transitions which leave the donors in the $2p_0$ and $2p_{-1}$ terminal excited states are observed to be the strongest. Moreover, only two transitions to the $2p_{-1}$ magnetic substate and one transition to the $2p_0$ magnetic substate are observed to have significant intensities in the "two-electron" satellite spectrum. The "two-electron" transition is not observed to be strong for every single principal line due to selection rules.

The high-resolution spectra of "two-electron" transitions were obtained by resonant excitation of one of the strong principal lines of (D°,X). Figure 2 shows the "two-electron" satellite spectra for the samples E and A. The top spectrum in Figure 2 for this sample was recorded with the dye laser output tuned to the line 'b' in Figure 1. The bottom spectrum was recorded for sample A grown by MOCVD (metalorganic chemical vapor deposition) with the dye laser output tuned into resonance with one of the strong principal lines, e.g., the line 'c' in this case. To identify the "two-electron" MPL peaks corresponding to particular donor species the results of MPL measurements at different magnetic fields have been correlated with the results of PTIS measurements on the same samples. This correlation along with the results of resonance excitation has been used to relate the "two-electron" satellite peaks to the principal lines. The principal line labeled 'b' in Figure 1 and the low-energy strong line labeled 'β' in the "two-electron" transition to the $2p_{-1}$ donor magnetic substate are found to be related to each other in that the same initial state is involved in both transitions. The correlation suggests that the single strong line in the "two-electron" transition to the

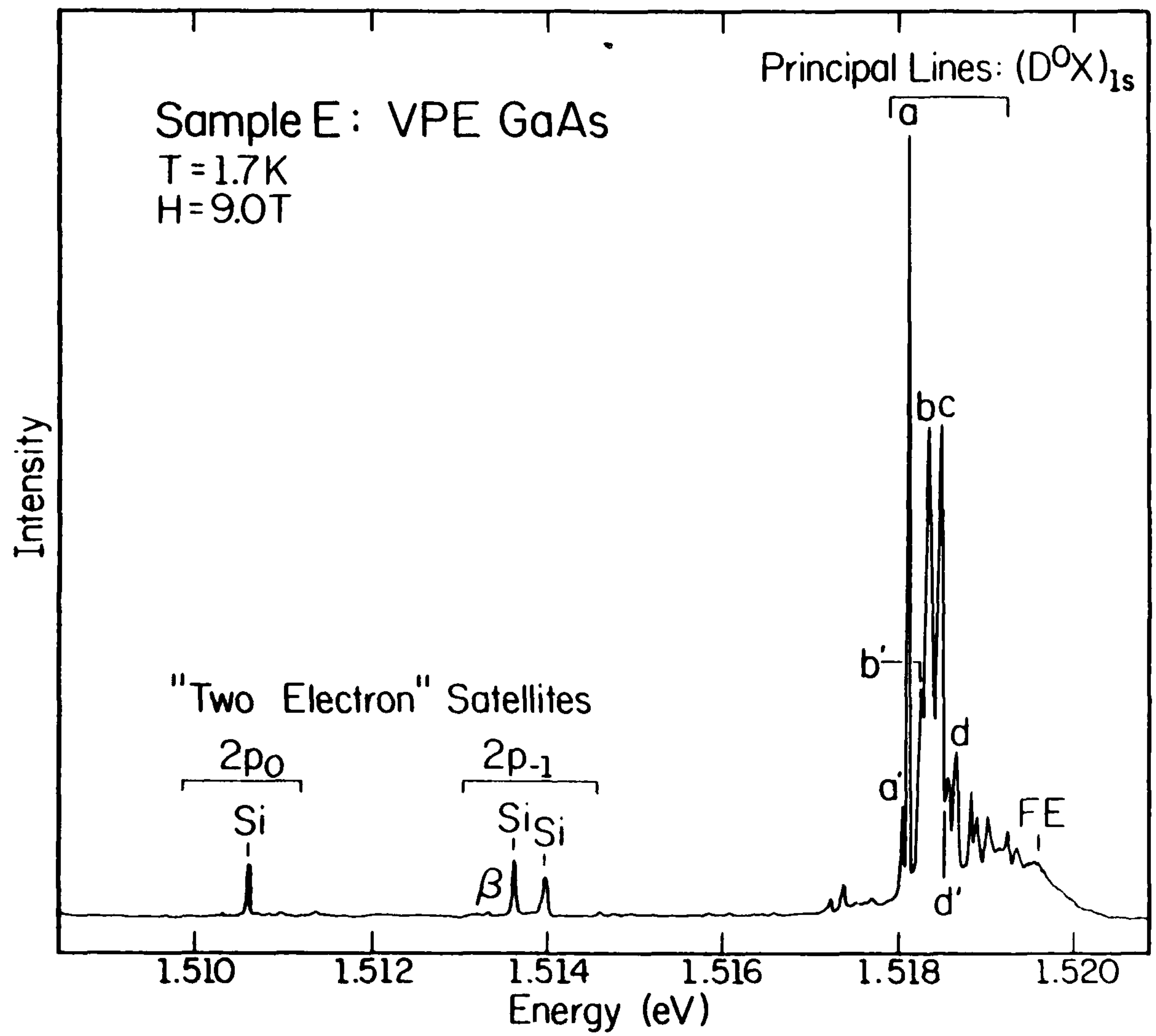


Fig. 1. Low temperature (1.7 K) photoluminescence (PL) spectrum of exciton recombination in high-purity $AsCl_3$–VPE GaAs at a magnetic field H = 9.0 T. The spectrum was recorded with the dye laser output tuned to near bandgap energy, 1.5220 eV. The principal lines lie on the high-energy side of the figure. To lower energy lie the "two electron" transitions which leave the donor in the $2p_{-1}$ and $2p_0$ terminal magnetic substrates. The Si donor is identified in this sample.

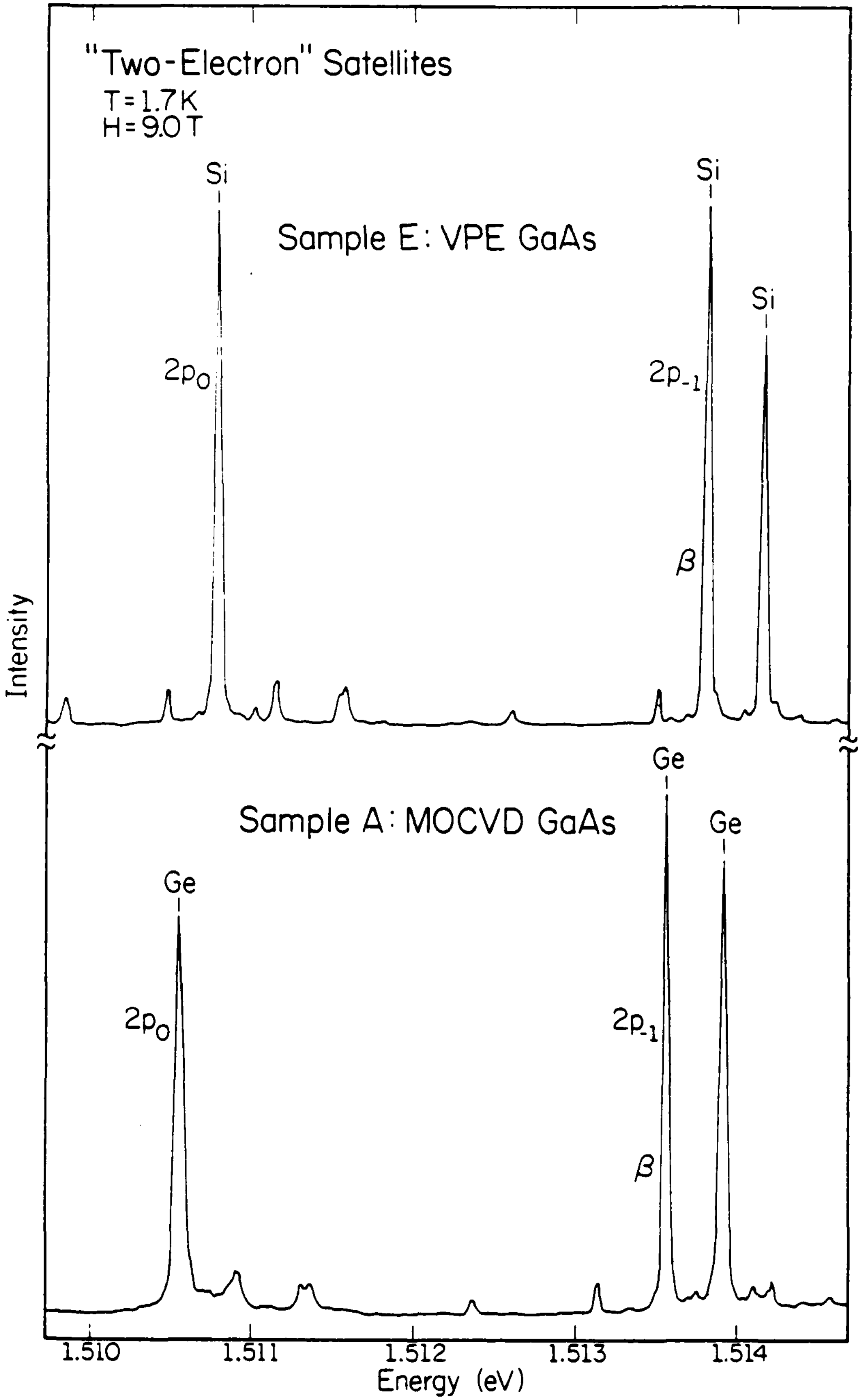


Fig. 2. "Two-electron" spectra for two GaAs samples recorded at a magnetic field H = 9.0 T with the resonant excitation of one of the strong principal lines. Si and Ge donors are identified in the samples E and A, respectively.

$2p_0$ donor magnetic substate is a "two-electron" replica of the principal line 'b' or a line close to 'b'. The energy separation between the principal line 'b' and the corresponding "two-electron" satellite peak ($2p_{-1}$ case) labeled 'β' gives the $1s-2p_{-1}$ energy for the donors. The principal line corresponding to the high-energy strong line in the "two-electron" transition to the $2p_{-1}$ donor magnetic substate is not observed. This unobserved principal line, which is very close to the line 'd', must be an unfavored transition because of the influence of the selection rules. The $1s-2p_{-1}$ energies can be used to identify donors from the MPL spectra. The donors identified in samples E and A from MPL spectra are Si and Ge, respectively. The dominant Ge donor in sample A has been identified from the correlation of PTIS measurements with MPL measurements. The identification of Si donors in the sample E is also consistent with the correlation. The $1s-2p_{-1}$ energies for Si and Ge donors measured from the MPL spectra for samples E and A are 4.64 meV and 4.87 meV, respectively, at a magnetic field of 9.0 T.

Figure 3 shows the "two-electron" satellite spectra for samples B, C, and D recorded at a magnetic field of 9.0 T with the dye laser tuned to a strong principal line for samples C and D. The spectrum for sample B was recorded with above bandgap excitation. The samples are very high-purity GaAs epitaxial layers grown by liquid phase epitaxy (LPE) and molecular beam epitaxy (MBE). S is identified as a dominant donor in the LPE GaAs sample B. The donors identified in the MBE GaAs sample C (lightly Si-doped) are S and Si. Also, S, Sn (Se), and Te donors are identified in the third LPE GaAs sample D. The $1s-2p_{-1}$ energies for Si and S donors measured from MPL spectra are 4.64 meV and 4.73 meV, respectively, at a magnetic field of 9.0 T.

The energy separation of the peaks due to different donors in the MPL spectra of the "two-electron" satellite gives the central cell shifts between the 1s (ground) states of the donors. The central cell shift between S and Si measured from the "two-electron" satellite spectrum for the MBE GaAs sample is 0.12 meV at a magnetic field of 9.0 T. The central cell shifts between S and Sn (or Se) donors and between S and Te donors measured from the satellite spectrum for the sample D are 0.09 meV and 0.18 meV, respectively, at a magnetic field of 9.0 T. The central cell shifts between donors, measured from the satellite spectra for samples in which more than one donor species have been detected, are little larger than what should be expected based on the correlation of PTIS measurements with MPL measurements.

All the major donors, S, Si, Ge, Sn (or Se), and Te are identified by magneto-photoluminescence measurements on the GaAs epitaxial layers grown by various techniques. These results manifest good correlation with the photothermal ionization spectroscopic measurements on the same epitaxial layers.

During the second year of this work, photoluminescence measurements by Fourier Transform spectroscopy will be developed. This should result in faster, higher resolution measurements and when developed will permit the photoluminescence study of narrow bandgap materials using the same technique.

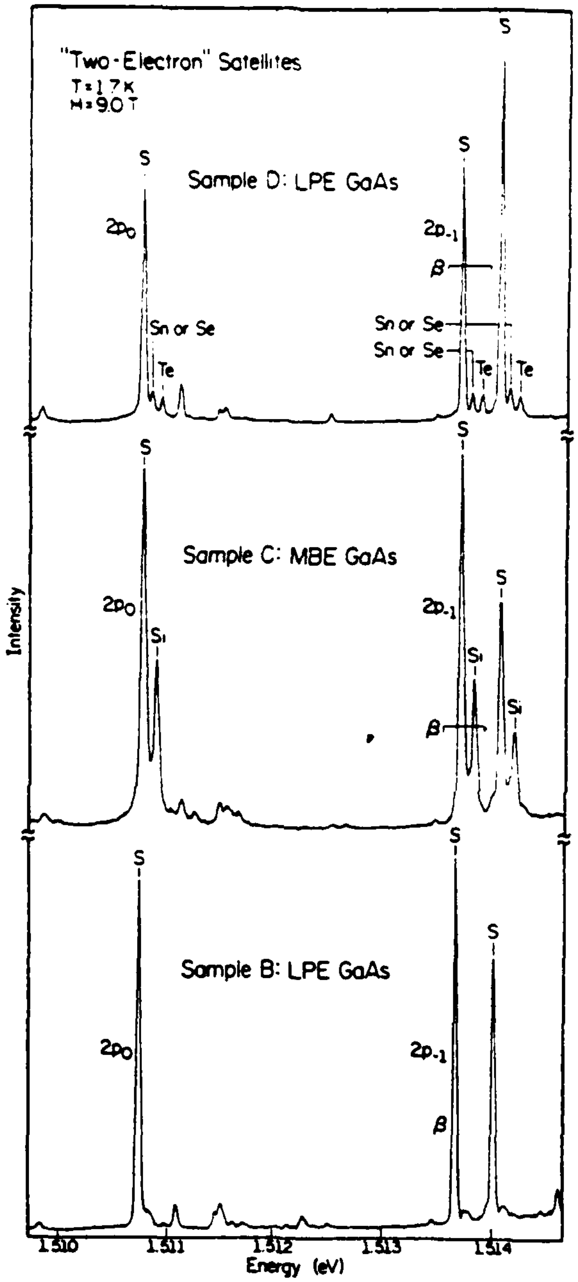


Fig. 3. "Two-electron" spectra for three GaAs samples recorded at a magnetic field of 9.0 T. The principal lines occur at nearly the same energies for these samples. Spectra for LPE and MBE GaAs samples show that the peaks due to S donors match in energy position and the peaks corresponding to Sn (or Se) and Te donors lie on both sides of the Si-peak.

PUBLICATIONS

[1] F. C. Larkins, E. S. Hellman, D. G. Schlom, J. S. Harris, Jr., M. H. Kim, and G. E. Stillman, "Reduction of the acceptor impurity background in GaAs by molecular beam epitaxy," *Appl Phys Lett.*, vol. 49, pp. 391-393, 1986. (DARPA/ONR)

[2] N. Pan, N. Tabatabaie, and G. E. Stillman, "LPE diffusion-limited growth of InGaAs," *J Crystal Growth*, vol. 78, pp. 97-104, 1986. (NSF-ECS/NSF-DMR)

[3] B. J. Skromme, S. S. Bose, and G. E. Stillman, "New shallow acceptor levels in GaAs," *J Electronic Mater.*, vol. 15, pp. 345-348, 1986. (AFOSR/DARPA)

[4] W. I. Wang, E. E. Mendez, Y. Iye, B. Lee, M. H. Kim, and G. E. Stillman, "High mobility two-dimensional hole gas in an $Al_{0.26}Ga_{0.74}As$/GaAs heterojunction," *J Appl. Phys.*, vol. 60, pp. 1834-1835, Sept. 1986. (AFOSR/DARPA)

[5] M. A. Haase, M. A. Emanuel, S. C. Smith, J. J. Coleman, and G. E. Stillman, "Band discontinuities in GaAs/$Al_xGa_{1-x}As$ heterojunction photodiodes," *Appl. Phys. Lett.*, vol. 50, pp. 404-406, Feb. 1987. (ONR/ARO)

[6] B. Lee, N. Pan, and G. E. Stillman, "Neutron transmutation doping of high purity InP," *J. Appl Phys* (to appear). (AFOSR/DARPA/NSF-DMR)

[7] T. R. Lepkowski, R. Y. DeJule, N. C. Tien, M. H. Kim, and G. E. Stillman, "Depletion corrections in variable temperature hall measurements," *J Appl Phys.* (to appear). (AFOSR/ONR/NSF-DMR)

WORK UNIT NUMBER 5

TITLE: Heterostructure Electronic Devices by Metalorganic Chemical Vapor Deposition (MOCVD)

SENIOR PRINCIPAL INVESTIGATOR:

J. J. Coleman, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. A. Emanuel, Research Assistant
T. K. Higman, Research Assistant

SCIENTIFIC OBJECTIVE:

The objective of this program is to extend to electronic devices the enormous impact that metalorganic chemical vapor deposition (MOCVD), as a sophisticated epitaxial growth method, has had on optical device research. This involves fundamental studies of the MOCVD process itself for electronic materials, studies of the electronic properties of heterostructure electronic materials, and studies of devices made from these materials. Three specific areas of interest for this research are (1) development of new reaction chamber designs and growth regimes for MOCVD-grown heterostructure electronic materials, (2) continuation of structural and materials analysis including deep-level transient spectroscopy (DLTS) and Shubnikov-de Haas measurements of superlattice structures, and (3) development of MOCVD-grown real space transferred electron devices and other electronic devices.

SUMMARY OF RESEARCH:

In the past year, we have developed the heterostructure hot electron diode (H^2ED), a new two-terminal device that exhibits S-shaped negative differential resistance (NDR) due to a field-dependent transition between the current conduction modes of tunneling and thermionic emission of hot electrons in a two-layer AlGaAs-GaAs heterostructure. Experimental results have been obtained for various single period and multiple period H^2ED structures fabricated from wafers grown by metalorganic chemical vapor deposition (MOCVD). We have shown, using an analytic theory, that the field-switching mechanism previously proposed is in fact responsible for the NDR observed in the heterostructure hot electron diode. In addition to the tunneling and thermionic emission of hot electrons, the accumulation of electrons at the heterointerface is identified as an important mechanism in the operation of the device. Experimentally, we verify that the basic physical requirements for switching predicted by the theory are correct and further we show that the potentially detrimental effect of impact ionization can be minimized by proper design. Preliminary investigations of the H^2ED on nonoptimized structures have resulted in test-fixture-limited oscillation at frequencies greater than 17 GHz. These results indicate that, as reported previously, the H^2ED should be capable of transit time-limited, high-speed performance.

JSEP-SPONSORED PUBLICATIONS

[1] T. K. Higman, M. A. Emanuel, J. J. Coleman, S. J. Jeng, and C. M. Wayman, "Structural analysis of Au-Ni-Ge and Au-Ag-Ge alloyed ohmic contacts on modulation doped AlGaAs-GaAs heterostructures," *J. Appl. Phys.*, vol. 60, p. 677, 1986. (JSEP/NSF)

[2] P. A. Martin, K. Hess, M. A. Emanuel, and J. J. Coleman, "Deep level transient spectroscopy studies of defects in GaAs AlGaAs superlattices," *J. Appl. Phys.*, vol. 60, p. 2882, 1986. (JSEP/ONR)

[3] K. Hess, T. K. Higman, M. A. Emanuel, and J. J. Coleman, "New ultrafast switching mechanism in semiconductor heterostructures," *J. Appl. Phys.*, vol. 60, p. 3755, 1986. (JSEP/ONR/ARO)

[4] S. J. Manion, M. Artaki, M. A. Emanuel, J. J. Coleman, and K. Hess, "Electron energy loss rates in AlGaAs/GaAs heterostructures at low temperatures," *Phys. Rev. B* (in press). (JSEP/ONR)

[5] T. K. Higman, J. M. Higman, M. A. Emanuel, K. Hess, and J. J. Coleman, "Theoretical and experimental analysis of the switching mechanism in heterostructure hot electron diodes," *J. Appl. Phys.* (in press). (JSEP/ONR/ARO)

WORK UNIT NUMBER 6

TITLE: High-Speed and Other Optical Properties of MBE-Grown Structures

SENIOR PRINCIPAL INVESTIGATORS:

M. V. Klein, Research Professor
H. Morkoc Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

D. Levi, Research Assistant

SCIENTIFIC OBJECTIVE:

Objectives are twofold. The first is to characterize and understand the optical and vibrational properties of novel semiconductor superlattices and multiple quantum wells. The second is to study and understand the dynamics of photopumped carriers in quantum wells.

SUMMARY OF RESEARCH:

The JSEP-supported portion of our work on Raman and other optical properties of semiconductor quantum wells and superlattices has consisted of two parts: (1) a Raman study of phonons in a GaAs-AlAs superlattice as the two components diffuse into each other upon high temperature annealing: and (2) setting up equipment for time-resolved absorption measurements of photopumped GaAs quantum wells.

Properties of Phonons in a GaAs-AlAs Superlattice upon Annealing

Since joining the JSEP program, we have used Raman scattering to study the effects of superlattice layering on the acoustical and optical phonons in semiconductors. Our earlier work has shown conclusively that very simple models apply to phonons having wavevector q normal to the interfaces. The longitudinal acoustical (LA) modes propagate freely through the interfaces, suffering only relatively weak Bragg reflection, and have dispersion curves given by minizone folding of the virtual-crystal dispersion curve. The longitudinal optic (LO) modes are strongly confined into either GaAs-rich or AlAs-rich regions and show little dispersion with q_z. We have now completed an extensive study of how these modes change when the concentration profile of the superlattice is changed by high-temperature annealing. That profile was measured using x-ray diffraction. The folded acoustic phonons did not shift in frequency but did change intensity upon annealing. The intensity of the two lowest doublets followed that of the two smallest superlattice diffraction peaks, in agreement with our photoelastic model for coupling of light to acoustic phonons in a superlattice. The third-order doublet was anomalously strong due, we believe, to a resonant enhancement of the photoelastic coefficient in Al-rich portions of the superlattice. We followed up to the ninth order of confined LO phonon modes. With annealing, they shift down in frequency due to an effective narrowing of the GaAs phonon quantum wells due to diffusion of Al. This can be quantitatively explained using an effective mass model for the phonons. The Al concentration profile generates the "potential energy" term in the wave equation through the known dependence of LO frequency on concentration. Known phonon dispersion for GaAs gives the "effective mass" term. These results show that a simple model exists for LO phonons in quantum wells and superlattices having a general concentration profile.

Instrumentation for Time-Resolved Absorption in Quantum Wells

In the Laser Laboratory of the Materials Research Laboratory, we have set up equipment that allows us to measure the change in absorption in quantum well samples produced by pumping carriers into the conduction subbands. With JSEP and other support, we have ordered a femtosecond, cavity-dumped dye laser that will extend our capability for time-resolved absorption measurements into the sub-picosecond regime.

Molecular Beam Epitaxy

During this period we have concentrated our efforts on understanding the material quality of (Al,Ga)As/GaAs and (In,Ga)As/GaAs multi-quantum well (MQW) structures on compound and elemental substrates grown by molecular beam epitaxy (MBE). Room temperature photoreflectance measurements were used in these studies. From the study of (Al,Ga)As/GaAs MQWs [9] grown on n± GaAs substrates, we have observed transitions involving the so called "unconfined" states, which have received less attention so far. The study of a low-barrier multiple quantum-well structure has allowed us to observe many transitions as far as 200 meV beyond the barrier gap.

The other photoreflectance studies [4,10] on the (Al,Ga)As/GaAs and GaAs/(In,Ga)As MQWs grown on Si and Ge have demonstrated that a variety of III-V compound devices can be grown on elemental substrates.

In a separate investigation we have studied the effect of annealing on the dislocation reduction near the interface of the GaAs/Si and in the bulk of GaAs layers [3]. We have demonstrated that ex-situ and in-situ annealing at higher temperatures reduces the threading dislocations considerably. This will aid in growing high quality active layers for high speed applications on Si substrates.

Finally, we have studied the mobility degradation in GaAs and (In,Ga)As [5], GaP [6] and (Al,Ga)As/GaAs [7] structures at high electric fields. We have shown that the asymmetry in the distribution function of the electrons is the cause of the mobility degradation. Furthermore, the mobility of high-mobility materials degrades faster with the electric fields than low-mobility materials.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] T. C. McGlinn, T. N. Krabach, M. V. Klein, G. Bajor, J. E. Greene, B. Kramer, S. A. Barnett, A. Lastras, and S. Gorbatkin, "Raman scattering and optical-absorption studies of the metastable alloy system $GaAs_xSb_{1-x}$," *Phys Rev. B*, vol. B33, pp. 8396-8401, 1986. (JSEP/NSF)

[2] D. Y. Oberli, D. R. Wake, M. V. Klein, J. Klem, and H. Morkoc, "Transient Raman scattering in multiple quantum well structures," in *Ultrafast Phenomena V*, G. R. Fleming and A. E. Siegman, Eds. Berlin: Springer, 1986, pp. 207-209. (JSEP/AFOSR/NSF)

[3] C. Choi, N. Otsuka, G. Munns, R. Houdré, H. Morkoc, S. L. Zhang, D. Levi, and M. V. Klein, "Effect of In-Situ and Ex-Situ annealing on dislocations in GaAs on Si substrates," *Appl. Phys. Lett.*, vol. 50, no. 5, pp. 992-994, 1987. (AFOSR/JSEP/NSF [MRL and MRG]).

[4] U. K. Reddy, G. Ji, R. Houdré, H. Unlu, D. Huang, and H. Morkoc, "Study of GaAs/AlGaAs and InGaAs/GaAs multiple quantum wells grown on non-polar substrates by photoreflectance," *Proc. of SPIE Conf.*, Mar. 1987, Florida, USA (in press). (NASA/JSEP/AFOSR)

[5] V. K. Arora, D. S. L. Mui, and H. Morkoc, "Mobility degradation and transferred electron effect in gallium arsenide and indium gallium arsenide" (to be published in *IEEE Trans. Elect. Dev.*). (JSEP/AFOSR)

[6] V. K. Arora, D. S. L. Mui, and H. Morkoc, "High-field electron drift velocity and temperature in gallium phosphide" (to be published in *J. Appl. Phys.*). (JSEP/AFOSR)

[7] V. K. Arora, D. S. L. Mui, and H. Morkoc, "Mobility degradation in a quantum-well heterostructure of GaAs/AlGaAs prototype" (to be published in *Appl. Phys. Lett.*). (JSEP/AFOSR)

[8] D. Y. Oberli, D. R. Wake, M. V. Klein, T. Henderson, and H. Morkoc, "Time-resolved Raman scattering in GaAs quantum wells" (to be published in *SPIE Proceedings*, vol. 793. (JSEP/AFOSR/NSF)

[9] U. K. Reddy, G. Ji, T. Henderson, H. Morkoc, and J. N. Schulman "Investigation of GaAs/(Al,Ga)As multiple quantum wells by photoreflectance" (to be published in *J. Appl. Phys.*, June 1987). (JSEP/AFOSR)

[10] U. K. Reddy, R. Houdré, G. Munns, G. Ji, H. Morkoc, M. Longerbone, L. Davis, B. P. Gu, and N. Otsuka, "Investigation of GaAs/(Al,Ga)As multiple quantum wells grown on Ge and Si substrates by molecular beam epitaxy" (submitted to *J. Appl. Phys.*). (JSEP/AFOSR)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] M. V. Klein, "Phonons in semiconductor superlattices," *IEEE J. Quant. Electron.*, vol. QE-22, pp. 1760-1770, 1986. (NSF)

WORK UNIT NUMBER 7

TITLE: Computer-Aided Design of High-Performance Integrated Circuits with Ultra-Small Features

SENIOR PRINCIPAL INVESTIGATORS:

I. N. Hajj, Research Professor
S. M. Kang, Research Associate Professor
V. B. Rao, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

K. R. Cioffi, Research Assistant
F. P. Lai, Research Assistant
D. Smart, Research Assistant
S.-L. Su, Research Assistant
A. T. Yang, Research Assistant

SCIENTIFIC OBJECTIVE:

The continuing evolution of integrated circuit processing technology toward ultra-small feature sizes and new compound semiconductor materials and devices demand new computer-aided design (CAD) tools and design methods. One of the basic issues is to develop efficient circuit models for new devices such as the High-Electron Mobility Transistor (HEMT) and important parasitics of interconnects in high-speed integrated circuits. With such models, integrated circuits can be simulated accurately. Apart from modeling, problems related to the chip yield and reliability, design verification of Ultra-/Very-Large Scale Integrated (U/VLSI) circuits by using novel parallel computation algorithms and hardwares, and the chip-performance optimization in view of yield and reliability are becoming issues of increasing importance.

The objectives of our research in this unit are:

(1) to develop a computationally efficient model for the HEMT and interconnection parasitics so that high-speed integrated circuits can be simulated accurately in short time;

(2) to develop rigorous design optimization techniques for yield and reliability enhancement; and

(3) to develop accelerated circuit simulation methods for U/VLSI circuits by exploiting hierarchy and parallelism.

SUMMARY OF RESEARCH:

This past year, a new physical model has been developed and implemented in the Illinois Simulator for Modeling of Integrated-circuit Level Elements (iSMILE) program, which was developed under the JSEP sponsorship. This model is charge-based and uses a novel analytical approximation of channel-charge versus gate-voltage characteristics, which renders a closed-form solution for the channel current. The model equations for the current and charge have continuous derivatives and hence are well-suited for circuit simulation. With accurate dc characterization of both enhancement and depletion devices, we have been able to predict ring oscillator circuit delays with less than 10% error. Device samples have been obtained from both AT&T Bell Laboratories

(Dr. S. S. Pei) and the Coordinated Science Laboratory (Prof. H. Morkoc.). The effects of parasitic capacitances and resistances have been investigated extensively to determine optimal device geometries for maximum circuit speed. By using our analytical equations for the gate fringing capacitance and the interelectrode capacitances, we can predict the optimal source-to-gate spacing which seems to match well with the current state-of-the- art devices.

This research will be continued in the coming year to extend the domain of the model to small-signal analysis of high-power microwave circuits. This would include the improvement and verification of the model with S-parameter measurements at different dc bias points and at many different frequencies. Also much more work needs to be done on the modeling of back-gate biasing effects and the gate-diode capacitance. Statistical analysis is also required to determine the effects of various process deviations on the device yield.

For the improvement of yield and reliability, we have developed a new hierarchical timing optimizer iJADE for MOS VLSI circuits. iJADE uses a switch- level timing simulator for accurate delay calculation and a rule-based expert system to optimally determine individual transistor sizes for speed-area trade-offs. iJADE takes in the SPICE input descriptions for the circuit to be optimized, partitions the circuit hierarchically to save the memory space, detects critical paths, and then finds optimal transistor sizes to meet the timing specifications. iJADE is written in Franz LISP language and at present consists of about 10,000 lines of code. It runs on the VAX-11/780 under the UNIX operating system. Several circuits have been tested with iJADE, and it has been demonstrated that iJADE could find a better circuit construct than a design-in-mask from industry containing more than 140 transistors. Also, iJADE was able to eliminate all the glitches in the industry design.

To make our circuit optimization system more versatile, this work needs to be continued in the coming year in order to test larger and more difficult examples. It is desirable to include a self-learning capability so the rules for circuit optimization can evolve automatically as iJADE is exercised for more difficult circuits.

Multiprocessors offer a way to reduce the time required to perform circuit simulations of large circuits. To obtain this speed advantage, the simulation algorithm must have sufficient concurrency to keep the processors usefully employed without introducing excessive memory contention and scheduling overhead. Future multiprocessors with larger numbers of processors, such as the Cedar machine which is to consist of multiple 8-processor Alliant FX/8 computers, will require algorithms with higher degrees of concurrency in order to achieve further speed improvements.

We have studied alternative strategies for employing waveform relaxation (WR) algorithms to perform circuit simulations of digital MOS circuits on multiprocessors. WR has a potential speed advantage due to its multirate integration properties, and it exhibits natural concurrency due to the inherent decoupling of the circuit into independently solved subcircuits.

To study the performance of alternative WR algorithms on an actual multiprocessor, we developed a WR circuit simulator to run on an 8-processor Alliant FX/8 computer. Both the Gauss-Seidel and Gauss-Jacobi methods are implemented. In the current version of the program, tasks are defined only at the time-window level. Circuits with up to 805 transistors have been simulated. The results demonstrate that when the number of processors is sufficiently large, the Gauss-Jacobi method generally outperforms the Gauss-Seidel method. The opposite is the case when the number of processors is small. The break-even point between the two methods is a function of the properties of the circuit being simulated.

To determine whether to use the Gauss-Seidel or Gauss-Jacobi method for a given circuit on a given number of processors, we have developed a computationally inexpensive algorithm which estimates the break-even point between the two methods. The break-even point calculation uses an estimate of concurrency based on the task precedence graph and task CPU times which are assumed to be proportional to subcircuit size.

The time-point pipelining strategy was first reported in the literature as a way to retain the fast convergence properties of the Gauss-Seidel method while at the same time improving its concurrency by synchronizing tasks at the time-point level rather than the time-window level. We have generalized the time-point pipelining algorithm and applied it to the Gauss-Jacobi method. In this algorithm, all subcircuits in all iterations can be solved concurrently, with only a slight delay from the start of one iteration to the start of the next iteration. The high degree of parallelism of this method is of particular interest as multiprocessors with larger numbers of processors become available.

A parallel simulation time estimation program—PARASITE—was developed to estimate the run times of WR simulations performed on any specified number of processors. PARASITE uses CPU times of individual tasks measured during an actual simulation run on a uniprocessor. It then simulates the assignment of tasks to processors and estimates the overall multiprocessor CPU time neglecting multiprocessing overhead. The results show that the Gauss-Jacobi method with time-point pipelining can outperform the Gauss-Seidel method with time-point pipelining if the number of processors is sufficiently large and if multiprocessing overhead can be kept sufficiently small.

We are currently implementing the generalized time-point pipelining algorithm in our multiprocessor WR program. The relationship between window size and time-point pipelining performance will be investigated. We also plan to study the use of parallel model evaluation in conjunction with the other strategies to alleviate bottlenecks which arise due to large subcircuits. The program will be adapted to run on the larger Cedar multiprocessor when it becomes available.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] R. D. Freedman, S. M. Kang, C. G. Lin-Hendel, M. L. Newby, "Extraction of SPICE circuit models from symbolic gate matrix layout with pruning," in *ACM/IEEE Design Automation Conf Proc.*, Las Vegas, NV, June 1986, pp. 418-424. (JSEP/AT&T)

[2] S. M. Kang and H. Y. Chen, "Modeling of propagation delay for a class of domino CMOS circuits," in *Proc. 29th Midwest Symp. on Circuits and Syst.*, Lincoln, NB, Aug. 1986, pp. 907-910. (JSEP/SRC)

[3] S. M. Kang, "Simulation of power dissipation in VLSI circuits," *IEEE J. on Solid-State Circuits*, vol. SC-21, no.5, pp. 889-891, Oct. 1986. (JSEP/SRC)

[4] K. R. Cioffi, A. Yang, T. N. Trick, and S. M. Kang," A charge-controlled circuit simulation model for MODFETs," *Workshop on Numerical Modeling of Processes and Devices of Integrated Circuits*, Palo Alto, CA, Nov. 1986. (JSEP)

[5] S-L. Su and V. B. Rao "A simple and accurate node reduction technique for interconnect modeling in circuit extraction," *IEEE Int. Conf. Comput.-Aided Design*, Santa Clara, CA, Nov. 1986. (JSEP)

[6] T. K. Yu, S. M. Kang, I. N. Hajj, and T. N. Trick, "Statistical modeling of VLSI circuit performances," *Digest of Technical Papers, IEEE Int. Conf. on Computer-Aided Design*, Santa Clara, CA, pp. 224-227, Nov. 1986. (JSEP/SRC)

[7] V. B. Rao and T. N. Trick, "Network partitioning and ordering for MOS VLSI circuits," *IEEE Trans. Comput.-Aided Design of Integrated Circuits and Syst.*, vol. CAD-6, No. 1 Jan. 1987. (JSEP/IBM)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[8] S. M. Kang and D. Chu, "CMOS circuit design for prevention of single-event upset," in *Proc. IEEE Int. Conf. on Comput. Design*, Port Chester, NY, Oct. 1986, pp. 385-388. (SRC/Sandia National Labs)

[9] A. J. Stein, D. G. Saab, and I. N. Hajj, "A special-purpose architecture for concurrent fault simulation," *IEEE Int. Conf. on Comput. Design, ICCD'86*, Oct. 1986. (SRC/Sandia National Laboratories)

[10] K. S. Arun and V. B. Rao, "A new principal-components algorithm for graph partitioning with application in VLSI placement problems," in *Proc. 20th Ann. Asilomar Conf. on Signals, Syst., and Comput.*, Pacific Grove, CA, Nov. 1986. (SRC)

[11] M. Desai and I.N. Hajj, "Block time-point relaxation algorithms for circuit simulation," *IEEE Conf. on Comput.-Aided Design*, pp. 88-91, Nov. 1986. (SRC)

[12] I.N. Hajj and D. Saab, "Switch-level logic simulation of digital bipolar circuits," *IEEE Trans. Comput.-Aided Design*, vol. CAD-6, no. 2, pp. 251-258, Mar. 1987. (SRC/TRW)

[13] S. M. Kang, "Circuit optimization for CMOS VLSI," in *Advances in Computer-Aided Engineering Design*, JAI Press, Inc. (to appear).

[14] V. B. Rao, D. G. Saab, I. N. Hajj, and T. N. Trick, *Switch-level Timing and Fault Simulation*, Hingham, MA: Kluwer Academic Publishers (to appear).

WORK UNIT NUMBER 8

TITLE: Collective Electronic Transport in Quasi One-Dimensional Systems

SENIOR PRINCIPAL INVESTIGATORS:

J. R. Tucker, Research Professor
J. W. Lyding, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. H. Miller, Jr., IBM Postdoctoral Fellow
W. G. Lyons, Research Assistant
R. E. Thorne, Research Assistant

SCIENTIFIC OBJECTIVE:

The goal of this research is to understand the basic mechanism of charge density wave (CDW) transport in the quasi-one-dimensional metals $NbSe_3$, TaS_3, and similar materials. The motion of CDWs represents the only known example of current flow by a moving quantum ground state, apart from superconductivity. John Bardeen has proposed that CDW acceleration in an electric field takes place via a Zener tunneling process [9] and that the ac response can be predicted by applying the photon-assisted tunneling theory originally developed for superconductor-insulator-superconductor (SIS) millimeter wave mixers [10]. If this interpretation is correct, CDW materials could become important systems for use as detectors and mixers, as well as for basic studies of macroscopic quantum tunneling. An extensive experimental program is conducted in our laboratory to characterize the dynamics of CDW motion and to test the predictions of the tunneling theory.

SUMMARY OF RESEARCH:

The past year has been unusually productive, with major progress in the following areas: (1) understanding the nature of the low-frequency dielectric relaxation behavior observed in CDW materials below the dc threshold field, (2) characterizing the effective pinning potential that gives rise to current oscillations and ac-dc interference phenomena for CDW motion above the dc threshold, and (3) the beginnings of a microscopic theory of CDW dynamics that demonstrates why tunneling is required for CDW acceleration.

Our work on dielectric relaxation [4] has resolved a major controversy and led to new understanding. Experiments at Bell Laboratories have characterized a dielectric relaxation frequency in $K_{0.3}MoO_3$, $(TaSe_4)_2I$, and TaS_3 which decreases with an Arrhenius behavior, $\omega_0 \propto e^{-T_0/T}$, at low temperatures. Workers at UCLA saw no evidence for this phenomenon in their low-frequency ac conductivity measurements. Our experiments confirmed the existence of this effect and showed that the temperature-activated behavior was the result of normal electron screening of CDW charge fluctuations associated with the polarization.

The work on current oscillations and ac-dc interference which we performed during the past year [1,2,5,6,7] has produced some spectacular results. By careful growth and mounting of $NbSe_3$ crystals, we have been able to demonstrate extraordinary coherence for CDW motion throughout the entire sample volume--at least an order of magnitude greater coherence than previous work. The results of our experiments demonstrate that the CDW experiences a highly nonsinusoidal effective potential when moving above threshold, and that the magnitude of this pinning potential remains constant up to the highest fields $F \sim 100\ E_T$ that can be experimentally applied. These results are most important because they conclusively invalidate the classical deformable model of CDW dynamics that has served as the paradigm for most work in this field over the past five years [5]. This lends great support to the tunneling interpretation, and it is not now clear whether any classical model can be brought into line with all our experimental results.

On the theory front, we have written a very long paper [8] which derives John Bardeen's original tunneling model [9] by employing some rather exotic methods in one-dimensional quantum field theory. This work clarifies the basic arguments for CDW tunneling and shows how phase coherence can be realized by analogy to the Josephson effect.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] R. E. Thorne, J. R. Tucker, J. Bardeen, S. E. Brown, and G. Grüner, "Phase-locking in charge density wave transport," *Phys. Rev B*, vol. B33, pp. 7342-7345, 1986. (JSEP)

[2] R. E. Thorne, W. G. Lyons, J. H. Miller, Jr., J. W. Lyding, and J. R. Tucker, "Current oscillations in charge density wave transport," *Phys. Rev. B*, vol. B34, pp. 5988-5991, 1986. (JSEP/NSF)

[3] J. R. Tucker, "Dynamics of sliding charge density waves," *Physica*, vol. 143B, pp. 19-23, 1986. (JSEP/NSF)

[4] J. R. Tucker, W. G. Lyons, J. H. Miller, Jr., R. E. Thorne, and J. W. Lyding, "Origin of the dielectric relaxation frequency in sliding charge density wave systems," *Phys. Rev.*, vol. B34, pp. 9038-9041, 1986. (JSEP/NSF)

[5] R. E. Thorne, J. R. Tucker, and J. Bardeen, "Experiment versus the classical deformable model of charge density waves," *Phys. Rev. Lett.*, vol. 58, pp. 828-831, 1987. (JSEP/NSF)

[6] R. E. Thorne, W. G. Lyons, J. W. Lyding, J. R. Tucker, and J. Bardeen, "Charge density wave transport in quasi one-dimensional conductors: I. Current oscillations," *Phys. Rev.*, vol. 35, pp. 6348-6359, 1987. (JSEP/NSF)

[7] R. E. Thorne, W. G. Lyons, J. W. Lyding, J. R. Tucker, and J. Bardeen, "Charge density wave transport in quasi one-dimensional conductors: II. Ac-dc interference phenomena," *Phys. Rev.*, vol. 35, pp. 6360-6372, 1987. (JSEP/NSF)

[8] J. R. Tucker and J. H. Miller, Jr., "Theory of charge density wave tunneling," *Phys. Rev.* (submitted 15 December 1986). (JSEP/NSF)

REFERENCES:

[9] J. Bardeen, "Theory of non-Ohmic conduction from charge density waves in $NbSe_3$," *Phys. Rev Lett.*, vol. 42, pp. 1498-1500, 1979; "Tunneling theory of charge density wave depinning," *Phys Rev Lett.*, vol. 45, pp. 1978-1980, 1980; "Macroscopic quantum tunneling in quasi one-dimensional metals. II. Theory," *Phys. Rev. Lett.*, vol. 55, pp. 1010-1013, 1985.

[10] J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," *Reviews of Modern Physics*, vol. 57, pp. 1055-1113, 1985.

WORK UNIT NUMBER 9

TITLE: An Investigation of Plasma and Chemistry Processes in Cylindrical Magnetron Plasma Discharges

SENIOR PRINCIPAL INVESTIGATORS:

J. A. Thornton, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

G. Y. Yeom, Research Assistant

SCIENTIFIC OBJECTIVE:

The overall objective of this research is to investigate fundamental plasma and chemistry processes in a type of magnetically confined discharge that has promise for reducing radiation damage during device processing by dry etching.

Program Organization

This program is organized around three specific objectives.

1) To investigate the basic plasma behavior in rf driven cylindrical magnetrons and the resultant plasma-surface reactions.
2) To explore the plasma chemistry that is operative in low pressure rf-driven magnetron etching plasmas, beginning with an examination of CH_4-H_2 and CF_4-O_2 plasmas.
3) To investigate magnetron reactive ion etching of Si with particular emphasis on radiation damage and on the basic surface chemistry that establishes selectivity and anisotropic etching.

SUMMARY OF RESEARCH:

The research is proceeding as described in our original proposal. There have been no changes in the overall technical objectives (described above), the direction, the participants or the resource allocation.

A plasma discharge apparatus has been designed, built and placed in operation, which is capable of being operated with cylindrical magnetion electrodes of the type used for reactive ion etching. The apparatus can accommodate magnetron electrodes of various diameters and is instrumented for making: (1) electrostatic probe measurements of the plasma and floating potentials and the electron density and energy, (2) retarding grid electrostatic analyzer measurements of energies of the ions bombarding the electrode and wall surfaces, (3) optical emission spectroscopy measurements of the electron excitation behavior in the plasma, and (4) mass spectroscopic measurements of the species produced in the plasma.

Fundamental studies of the basic plasma behavior in rf-driven cylindrical magnetron discharges have been completed. Argon and He were used as working gases. In addition to providing fundamental information, which is being prepared for publication [1-6], these studies have provided guidelines for the reactive ion etching studies that are presently underway. In particular, the investigation has shown that the differences in current-voltage behavior between dc and rf driven magnetrons, and the differences in the tendency to develop a dc electrode bias that is seen when comparing rf driven cylindrical magnetrons with rf driven planar diode discharges of the type commonly used in plasma etching, can be explained in terms of the electron transport across the magnetic field. The dc bias behavior is significant in the context of plasma etching because it affects the energy distribution of ions which are incident on the various surfaces in contact with the plasma. Because the dc bias is dependent on the electron transport across the magnetic field, it can be influenced by both the magnetic field strength and its configuration. The ion energy distributions that were measured with the retarding grid electrostatic analyzers in our experiments, and which contributed to the above conclusions, were consistent with the measured plasma potential distribution and with the sputtering which occurred when Ar was used as a working gas.

Theoretical computer studies have been completed to assist in the data interpretation. These studies, which apply to both magnetrons and plasmas diodes, are being prepared for publication [6]. They show the importance of the discharge frequency and explain much of the data that has been reported in the literature. Similar studies relating to non-magnetron discharges are underway at the University of California [7].

Based on these observations, the discharge apparatus has been specifically configured for reaction ion etching experiments in which wafer etching stations and electrostatic analyzers are located on both the central and wall electrodes. The immediate objective in the experiments that are presently underway is to examine the ion energy distributions that are produced in CF_4-O_2 and CH_4-H_2 etching gases, their effectiveness in etching Si and SiO_2 respectively, and their influence on substrate surface damage as measured by capacitance-voltage methods.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] A. S. Penfold, G. Y. Yeom, and J. A. Thornton, "A new method for generating uniform magnetic fields in form suitable for cylindrical magnetron sputtering sources," in preparation. (JSEP)

[2] G. Y. Yeom and J. A. Thornton, "Current-voltage characteristics for DC and RF driven cylindrical magnetron discharge sources," in preparation. (JSEP)

[3] J. A. Thornton and G. Y. Yeom, "An examination of the current-voltage behavior of magnetron and planar diode discharge sources used for materials processing," in preparation. (JSEP)

[4] G. Y. Yeom and J. A. Thornton, "The formation of DC bias in RF driven cylindrical magnetron discharge sources," in preparation. (JSEP)

[5] J. A. Thornton, "RF driven cylindrical magnetron discharge sources," Keynote Address to be presented at 1987 Annual Symposium of the upstate New York Chapter of the American Vacuum Society, Rochester, New York, June 17-19, 1987 (invited). (JSEP)

[6] J. A. Thornton and G. Y. Yeom, "Voltage division versus area ratio considerations for RF driven plasma discharges," in preparation. (JSEP)

REFERENCE:

[7] S. E. Savas, "Estimating Ion impact energies and self bias voltages in low pressure RF discharges," paper presented at MRS Spring Meeting, Anaheim, CA, April 20-24, 1987.

WORK UNIT NUMBER 10

TITLE: Excited State Chemistry in Gases

SENIOR PRINCIPAL INVESTIGATORS:

J. G. Eden, Research Professor
J. T. Verdeyen, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

C. C. Abele, Research Assistant
J. Beberman, Research Assistant
G. Hebner, Research Assistant
K. J. Nordheden, Research Assistant
L. Overzet, Research Assistant

SCIENTIFIC OBJECTIVE:

Excited states and/or free radicals, produced by a gas discharge or an intense laser beam, play a critical role in the etching and deposition of semiconductor material. One case, dry processing with plasmas, has become the "standard" industrial tool, and much of the imaginations involving laser interactions are beginning to bear fruit. Inasmuch as these sources of radicals and excited states produce an environment which is far from that described by equilibrium thermodynamics, one can expect unique, puzzling, and yet most interesting processes resulting from the use of these techniques. Our goals have been and continue to be the understanding of the complex processes responsible for those actions and a development of a scientific model which quantifies the interaction between the source (electrons or photons), the donor gas, and the semiconductor surface. We will continue the basic study of the kinetic processes occurring in these environments, but we also plan to combine the two technologies.

A further objective is to exploit novel photochemical processes in the gas phase for the growth of metal and semiconductor films. Particular emphasis will be placed on the use of multiphoton ionization (MPI) of Column IIIA metal alkyls for the growth of compositionally and doping-modulated III-V film structures.

A specific target for this next period is to combine the discharge, with its ability to produce copious quantities of free radicals in almost anything rather easily, with the laser, which has the advantage of energy selectivity and directionality, to gain further insight into these complex processes.

SUMMARY OF RESEARCH:

Plasma Processing

Completed Work -- During the past year we have completed our study of the effects of an Oxygen additive on the silicon etching characteristics of discharges in NF_3. This work was published in the *J. Electrochemical Society*. While there are still unknowns about the chemistry of such discharges, it appeared to be the optimum time to concentrate our efforts on the effects of RF modulation on the growth of a-Si:H.

Current work -- The past year's work has documented the parameter space for the growth of hydrogenated low bandgap amorphous silicon films using a modulated RF discharge. A side-by-side comparison of film properties of those grown with conventional CW RF discharges and those with a modulated one shows the superiority of the latter films: lower bandgap, higher density, higher activation energy, and as good, if not better, photoconductivity.

The striking difference between these films is best illustrated by Figure 1, which is a Tauc Plot showing the optical absorption as a function of the photon energy. The extrapolation of the straight-line portion back to the intercept is the bandgap and thus there is a significant reduction in it by the simple expedient of square-wave-modulating the RF discharge excitation. This is the only change: everything else is the same: system-parallel plane excitation; pressure ~1 torr, gas mixture - 0.5% SiH_4 in He; flow, peak-to-peak RF voltage; peak power; and substrate temperature.

Table 1 presents this side-by-side comparison of the films grown with a modulated discharge to that using a CW one with the major variable between the entries being the substrate temperature. One usually requires a high substrate temperature ~250°C in order to reduce the bandgap--a trend which is observable from the table. But also evident is the fact that the bandgap is **insensitive** to substrate temperature for modulated discharges. Indeed, the films grown at room temperature in this manner are just about as good as those with T = 250°C. This could be technologically important because it would permit a nearly infinite variety of substrates for practical applications.

Unfortunately, our scientific base for the effect is still in its formative phase. We have documented some very important facts about such discharges, which have led to reasonable, but, as yet, unproven hypotheses. For instance, modulation appears to change the kinetics somewhat of any plasma processing step, etching or growth. This suggests that ion bombardment may be preparing the surface sites during the "on" time and the surface chemistry dominating during the "off" period.

We do know that a copious amount of disilane is produced in these discharges and that it is **not** responsible for the very contorted time history of the bulk electron density. We have also made some detailed measurements on the electron kinetics of such discharges. Our major task for the coming year is to mold these separate bits of information into a reasonable model.

Laser Growth of Films

In the past year, the experimental effort has been two-pronged. Laser photochemical vapor deposition (LPVD) experiments have continued in which Si_2H_6 or GeH_4 is pyrolyzed while the substrate is illuminated with fluence (< 10 mJ $-$ cm^{-2}) of ultraviolet laser radiation. The film growth rate is clearly enhanced, even for very low optical fluences (1$-$2 mJ $-$ cm^{-2}). TEM and SNMS studies are being carried out of the structural (crystalline) and chemical characteristics of the grown films. By altering the laser wavelength, repetition frequency, and pulse energy, it has also been demonstrated that the species primarily responsible for film growth can be determined solely by the laser, and the reactor chemistry changed at will.

In the second set of experiments, a turbomolecular pumped reactor suitable for the growth of metal or semiconductor films from atomic ions produced by multiphoton ionization has been constructed. We are currently investigating the scaling of the Al^+ ion production rate with laser intensity when $Al_2(CH_3)_6$ is ionized in the blue. Similar studies will soon be underway with gallium.

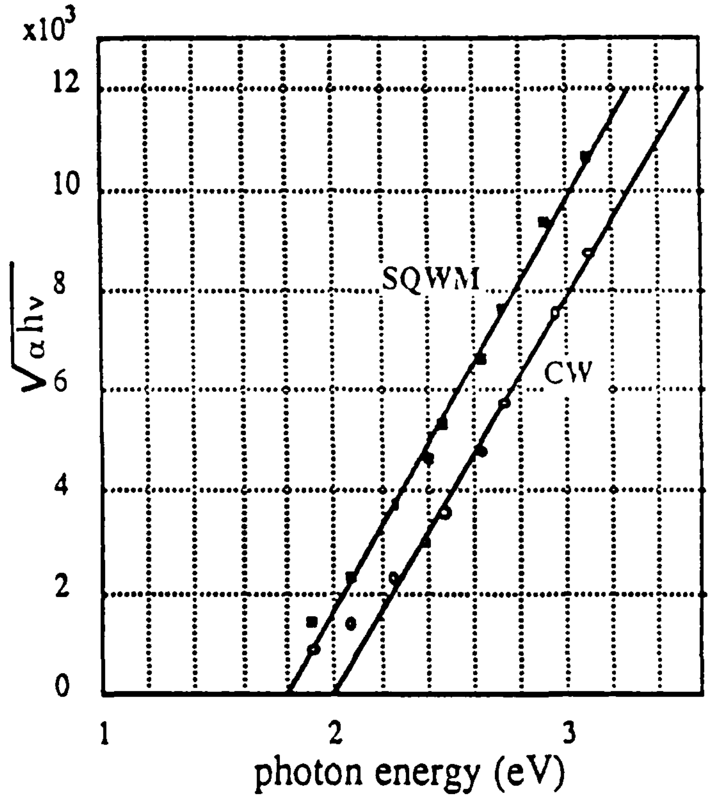


Fig. 1. A Tauc plot showing the typical differences between films deposited from continuous (CW) and modulated (SQWM) discharges (200 Hz modulation frequency)

Table 1. The optical and electrical properties of films produced in CW and SQWM discharges (200 Hz modulation frequency). (* data unavailable)

CW/ SQWM	Substrate Temperature (°C)	Refractive Index (at 1μm)	Optical Bandgap (eV)	Dark Conductivity $(\Omega*cm)^{-1}$	AM1 Conductivity $(\Omega*cm)^{-1}$	Activation Energy (eV)
CW	160	2.71	2.00	4.6 E-13	3.0 E-07	0.92
SQWM	155	3.09	1.82	6.8 E-12	1.8 E-07	0.87
CW	200	3.01	1.89	*	1.7 E-0.6	0.35
SQWM	200	3.08	1.84	2.2 E-11	3.9 E-06	0.85
CW	235	3.04	1.94	3.1 E-12	1.9 E-06	0.88
SQWM	255	3.15	1.81	1.2 E-11	1.3 E-06	0.84
CW	300	3.11	1.82	4.9 E-11	7.5 E-06	0.84
SQWM	300	3.13	1.82	1.3 E-11	1.3 E-06	0.33

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] J. G. Eden, "Photochemical processing of semiconductors: New applications for visible and ultraviolet lasers," *IEEE Circuits and Devices*, vol. 2, pp. 18-24, Jan. 1986. (JSEP)

[2] J. G. Eden, K. K. King, E. A. P. Cheng, S. A. Piette, and D. B. Geohegan, "Laser photochemical vapor deposition," *Proc. SPIE*, vol. 710, pp. 43-45, Sept. 1986. (JSEP)

[3] K. J. Nordheden and J. T. Verdeyen, "The effect of Oxygen on the etch rate of NF_3 discharges," *J Electrochem. Soc.*, vol. 133, pp. 2168-2171, 1986. (JSEP)

[4] L. J Overzet, J. T Verdeyen, R. M. Roth, F. F. Carasco, "The effects of modulation on a RF discharge in Silane and on the deposited a-Si:H," *MRS Symposium K*, Annaheim, CA (to be published). (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[5] M. N. Ediger and J. G. Eden, "Excitation spectroscopy of Kr_2 Rydberg states," *Chem. Phys. Lett*, vol. 126, pp. 158-162, May 1986. (NSF)

[6] D. P. Greene, K. P. Killeen, and J. G. Eden, "$X^2\Sigma \rightarrow B^2\Sigma$ absorption band of HgBr: Optically pumped 502 nm laser," *Appl Phys. Lett.*, vol. 48, pp. 1175-1177, May 1986. (NSF/AFOSR)

[7] K. P. Killeen and J. G. Eden, "Gerade Rydberg states and ns $^3\Sigma_u{}^+(1_u, 0_u^-)$ photoionization spectra of the rare gas dimers (n = 2 - 6)," *J. Chem. Phys.*, vol. 48, pp. 6048-6074, June 1986. (NSF)

[8] M. N. Ediger and J. G. Eden, "Excitation spectra of the np $^3\Pi_g$, n'p $^3\Sigma_g^+ \leftarrow$ 5s $^3\Sigma_u^+ (1_u, 0_u^-)$ Rydberg series of Kr_2," *J. Chem. Phys.*, vol. 85, pp. 1757-1769, Aug. 1986. (NSF/Los Alamos National Laboratory/ONR)

[9] D. P. Greene, K. P. Killeen, and J. G. Eden, "Excited state, charge transfer absorption spectrum of HgBr in the blue ($\lambda \sim 447$ nm)," *J. Chem. Phys.*, vol. 85, pp. 3188-3193, Sept. 1986. (NSF)

[10] D. B. Geohegan, A. W. McCown, and J. G. Eden, "Absolute photoionization cross sections for Kr(5s) and Kr_2 5s $^3\Sigma_u^+(1_u, 0_u^-)$ excited states at 248 nm," *J. Chem. Phys.*, vol. 86, pp. 577-587, Jan. 1987. (NSF/ONR)

WORK UNIT NUMBER 11

TITLE: Monolithic Millimeter-Wave Integrated Circuits with Microstrip Antennas

SENIOR PRINCIPAL INVESTIGATORS:

S. L. Chuang, Assistant Professor
Y. T. Lo, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. Y. Han, Research Assistant
B. Do, Research Assistant

SCIENTIFIC OBJECTIVE:

Our principal goal on the investigation of monolithic microwave integrated circuit (MMIC) is to integrate active solid state devices with microstrip antennas. During the past year, progress has been made in the study of propagation characteristics of guidance structures, the coupling between waveguides and the integration of solid-state amplifiers with microstrip antennas.

SUMMARY OF RESEARCH:

Propagation Characteristics of Guidance Structures

The theoretical modeling in obtaining the propagation characteristics for a guidance structure would permit the design of a proper matching network to the device and optimum feeding to the antenna. Since the analysis of the guidance problem plays an important role in the design, considerable amount of effort must be expended on the numerical solution. A computer program using the finite element method has been developed to analyze the propagation constants for dielectric waveguide and microstrip lines. The program has the advantage of being able to handle complicated guidance geometries as compared to conventional techniques such as the effective index method, and it gives better results near cutoff frequency. However, a large amount of computational time and memory space is required when executing the program. Ten hours of supercomputer CPU time have been granted to work on this project, and future analyses are expected to be done on the CRAY.

Coupling between Waveguides

During the past year, we have been studying the applications of the strongly coupled-mode theory to optical waveguide couplers. The field distribution and the propagation constants were evaluated using the coupled-mode theory and compared with those obtained from the numerical approach and the weakly coupled-mode theory. The differences between these data were investigated, and we conclude that the strongly coupled-mode theory is a better method as compared to the weakly coupled-mode theory under either strong or weak coupling conditions. The theory was excellent in calculating the wave distribution and the energy levels for coupled quantum wells under equilibrium conditions and under the influence of an applied electric field. The coupled quantum well model is useful for novel electronic devices such as resonant tunneling diodes, which have the potential for millimeter-wave generation.

Integration of Amplifier to Microstrip Antennas

Our current research involves the use of the coplanar transmission line as a means of monolithically integrating solid-state devices, such as phase shifters and FETs, with an array of microstrip patch antennas. Due to the novelty of the coplanar line for millimeter-wave applications, much of our efforts have been spent on analytically and experimentally characterizing coplanar structures for amplifier design as well as for electromagnetically feeding the antenna array.

We have developed a computer program which can quasistatically calculate the impedance and effective dielectric constant of buried and unburied coplanar and microstrip transmission lines. We are currently extending our theoretical analysis to a full-wave analysis so that the frequency dependence of the lines may be determined. Experimentally, we have demonstrated the feasibility of using a coplanar line in monolithic design by fabricating and testing an integrated amplifier patch antenna prototype using coplanar lines. Currently, we are making a comparative study of several different methods of feeding microstrip antenna arrays using microstrip and coplanar slot line feeds. This includes comparisons of cross polarization, directivity, input impedance and parasitic radiation from the coplanar line and slot line. In addition, we are developing a novel measurement technique which can be used to characterize accurate coplanar fixtures. Such characterization is essential to the accurate measurement of transistor S-parameters, antenna input impedance, and coplanar discontinuities for amplifier design. This measurement technique also has potential significance in the field of microwave measurements due to its simplicity and cost.

PUBLICATIONS

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[1] M. Davidovitz and Y. T. Lo, "Study of the microstrip line feed as an integral part of the microstrip antenna," *1986 National Radio Science Meeting Digest*, June 8-13, 1986. (NASA, Lewis Research Center)

[2] M. Davidovitz and Y. T. Lo, "Input impedance of a probe-feed microstrip antenna with thick substrate," *IEEE Trans. Antennas Propagat.*, vol. AP-34, pp. 905-911, July 1986. (RADC)

[3] M. Davidovitz and Y. T. Lo, "Cut-off wavenumbers and modes for annular cross-section waveguide with eccentric inner conductor of small radius," to appear in *IEEE Trans. Microwave Theory Tech.*, 1987. (RADC)

[4] M. L. Oberhart and Y. T. Lo, "A new simple feed network for an array module of four microstrip elements," to appear in *Electron. Lett.*, 1987. (NASA, Lewis Research Center)

[5] Y. T. Lo, Editor-in-chief, *Handbook of Antenna Theory and Design*, Van Nostrand (to be published).

WORK UNIT NUMBER 12

TITLE: Investigation of Radar Scattering Characteristics of Controllable Surface Shapes with Application to Low Observable Targets

SENIOR PRINCIPAL INVESTIGATORS:

R. Mittra, Research Professor .

SCIENTIFIC PERSONNEL AND TITLES:

A. Peterson, Visiting Assistant Professor
Z. Pantic, Visiting Research Associate
A. Ali, Graduate Student
C. Chan, Graduate Student
A. Chang, Graduate Student
T. Cwik, Graduate Student
R. Gordon, Fellow
R. Hall, Graduate Student
R. Jorgenson, Fellow
J. Joseph, Graduate Student
K. Merewether, Graduate Student

SCIENTIFIC OBJECTIVE:

There are three principal objectives of this effort. The first is to develop efficient integral equation and differential equation techniques for solving the problems of electromagnetic scattering, and coupling into complex structures. The second is to study techniques for reducing the radar cross-section of targets of different shapes. The third is to analyze frequency selective surfaces (FSS) for radomes and other antenna applications.

SUMMARY OF RESEARCH:

During the past twelve months, we have successfully solved a number of radar scattering problems for bodies whose dimensions are large compared to the wavelength of the illuminating field. We have investigated both the iterative methods, e.g., the conjugate gradient method, the spectral iterative technique and the generalized Neumann series, and noniterative techniques, e.g., the spectral Galerkin method and the moment method. We have carried out a comparative study of the scope of application and the numerical efficiency of these techniques by solving some representative test problems. Two examples of such test problems are a large thin plate and a long missile-shaped body of revolution. An important aspect of the RCS study has involved the investigation of the multiple incident angle problem where the aspect angle of the incident field is varied over a wide angular range, e.g., from normal incidence to grazing. Because the body dimensions can be large compared to the wavelength, the number of unknowns employed in the representation of the induced current on the scatterer can reach up to several thousands when subdomain basis functions are employed. The resulting equations are typically solved using one of the iterative techniques because their use can circumvent the storage problem usually associated with conventional matrix elimination schemes when a large number of unknowns are involved.

Despite the storage advantage, the iterative techniques do suffer from one serious drawback in that they are very inefficient for solving the multiple excitation problem. For this reason, we have also investigated the possibility of reducing the number of unknowns in the representation of the current by employing the entire domain type of basis functions. We have demonstrated that a reduction of the number of unknowns by an order of magnitude, or even more, is possible by using an appropriate set of entire domain functions. Using these functions, we have been able to solve plate sizes as large as six wavelength square, with less than only 300 unknowns, i.e., with the number of unknowns at least an order of magnitude less than that required in the subdomain formulation We are currently studying the susceptibility of the solutions generated in this manner to the computer round-off errors. This study is important because the condition numbers of matrices generated by using the entire domain basis functions is often much larger than those obtained when the subdomain basis functions are employed. Hence, the matrix for the entire domain case is usually ill-conditioned. Methods for alleviating this difficulty are currently under investigation and the preliminary results look very promising.

In addition to the plate problem, we have been investigating the body of revolution (BOR) problem, which plays an important role in modeling a number of canonical radar targets. We have developed the theoretical analysis and the computer program based on this analysis for a BOR coated with one or more layers of lossy dielectrics. Numerical results have been generated for differently shaped bodies, e.g., cylinders, spheres, cones, and combinations thereof, and the results have been compared with those reported elsewhere. Body sizes up to 10 wavelengths have been analyzed with good success.

The problem of mutual coupling between antennas mounted on arbitrarily shaped cylinders is an important one from the point of view of estimating the degree of interference between two antennas located, say, on the fuselage or the wing of an airplane. This problem can be difficult to solve using the asymptotic techniques, e.g., the geometrical theory of diffraction (GTD), even when the size of the cylinder is large compared to the wavelength. We have developed numerical techniques for solving this problem and have generated results for some representative choice of parameters for the antennas and the cylinder.

Finally, we have developed iterative techniques for solving the problem of frequency selective screens comprised of a periodic array of arbitrarily shaped patches or apertures. The program is capable of handling a large number of unknowns and FSS elements with arbitrary geometries.

We are also studying the effect of truncating the doubly periodic screens and are evaluating the effects of this truncation on the scattering properties of this screen. Another aspect of our study involves the investigation of the out-of-band scattering characteristics of these screens. These characteristics are of interest from the point of view of designing satellite antenna systems with low RCSs. We are also investigating the effect of curvature on the frequency selective properties and the scattering characteristics of FSS screens. The curved FSS problem is important in the design of radomes.

A comparative study of various techniques for solving large-body scattering problems has been made, and some definitive conclusions regarding the relative advantages and disadvantages of these techniques have been reached. A spectral Galerkin approach has been developed for the purpose of reducing the number of unknowns and has been successfully applied to large-body-scattering problems. The problem of estimating the mutual coupling between antennas mounted on airplanes or missiles has been studied. Frequency selective surfaces with arbitrary elements have been investigated and the study of truncated as well as conformal FSSs has been initiated.

JSEP-SPONSORED PUBLICATIONS

[1] G. M. Wilkins and R. Mittra. "Dielectric antennas for millimeter-wave applications." EMC Technical Report No. 86-5, May 1986. (JSEP/ARO).

[2] R. Mittra. "Some recent developments on iterative techniques for solving electromagnetic scattering problems." *Proc. 1986 URSI Inter. Symp. on Electromagnetic Theory*, pp. 370-373, Budapest, Hungary, Aug. 1986. (JSEP/ONR)

[3] Z. Pantic and R. Mittra. "Quasi-TEM analysis of microwave transmission lines by the finite-element method." *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, no. 11, pp. 1096-1103, Nov. 1986. (JSEP/ARO/ONR)

[4] A. F. Peterson and R. Mittra. "Convergence of the conjugate gradient method when applied to matrix equations representing electromagnetic scattering problems." *IEEE Trans. Antennas Propagat.*, vol. AP-34, no. 12, pp. 1447-1454, Dec. 1986. (JSEP/ONR/ONR FELLOWSHIP)

[5] W. L. Ko and R. Mittra. "Scattering by a truncated periodic array." CSL Technical Report, UILU-ENG-87-2217, Mar. 1987. (JSEP)

WORK UNIT NUMBER 13

TITLE: High-Performance Testable Electronic Systems

SENIOR PRINCIPAL INVESTIGATORS:

J. A. Abraham, Research Professor
J. H. Patel, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

J. Gerstenberger, Graduate Research Assistant
S. Laha, Graduate Research Assistant
M. Malkawi, Graduate Research Assistant

SCIENTIFIC OBJECTIVE:

This unit seeks to develop, model, and analyze efficient, high-performance, and testable computer architectures which will exploit compound semiconductor technology. There has been increasing interest in the use of compound semiconductor technologies, such as gallium arsenide (GaAs), as a vehicle to develop high-performance electronic systems. Various studies have indicated that GaAs devices will become a larger share of the semiconductor market in the coming years. In addition to the high performance possible, the capability for greater radiation hardness in the compound semiconductor technology is of great interest to military systems. We have identified several aspects of computer architecture for particular attention, due both to their emerging importance from a technology-driven point of view, and to the lack of known structures or analysis techniques for meeting our objective.

SUMMARY OF RESEARCH:

Memory Organizations

Trace-driven simulation is a simple way of evaluating cache memory systems with varying hardware parameters. To evaluate realistic workloads, simulating even a few millions of addresses is not adequate and such large-scale simulation is impractical from the consideration of space and time requirements. Therefore, simply reporting some more simulation results on cache memories, which is found in profusion in existing literature, is not the goal of this research. The goal of this research is to develop new methods of simulation based on statistical techniques for decreasing the need for large trace measurements and to predict true program behavior. In the proposed method, sampling techniques are applied while collecting the address trace from a workload. The *cost* of the sampling-based simulation method in terms of both memory space and computer time is *significantly lower* than conventional techniques. For a trace length of 5 million references, this method typically requires collecting only 7% or less of the trace for smaller caches. For large caches, much longer segments of traces are required by conventional methods. The new method estimates the true value of miss ratio with much lower overhead. This technique gives *accurate* estimates of both the *mean value* and the *distribution* of the miss ratio.

The basic sampling technique that has been established is applicable to small caches. It is based on the assumption that caches are flushed totally during context switches. This is essentially true for smaller caches. The distribution of the miss ratio of the samples gives a reasonably accurate estimate of that of the cold-start miss ratio over the entire trace for the same context switch interval as the sample size. It has been experimentally shown for a varied class of programs that about 35 samples are adequate to well characterize the program behavior. The distribution of the miss ratio obtained by the sampling technique is compared with that from the simulation of the corresponding continuous trace by means of statistical techniques to validate the sampling-based simulation method.

The method, mentioned above, predicts the miss ratio of programs with context switch interval, equal to the sample size. A model is proposed to statistically project the results to different context-switch intervals from only one simulation of samples of a fixed size. The validity of this projection has been experimentally established. This model is also extended to predict the miss ratio of continuous tasks when the program runs to completion without any context switching.

The large caches are becoming very common and their behavior can only be studied by using massively long traces. But, the above sampling-based methods are not applicable to large caches where significant amounts of data are retained across the context switches. Therefore, a new concept of *primed cache* is introduced to simulate large caches by the sampling-based method. This is achieved by simulating only those portions of the cache whose true state can be recreated even from the sampled trace. Both direct-mapped and set-associative caches, as large as 128 Kbytes, have been studied using these methods.

Parallel Pipelined Architectures

We have been studying new techniques for accurate performance estimation of VLSI chips. This is a crucial problem in the design of very high-speed systems which include parallel pipelined architectures. Current techniques are limited in two respects. First, SPICE-type simulations are impractical due to the excessive CPU time required to simulate large chips. Second, less accurate timing simulators tend to calculate the absolute worst-case path, without regard to whether this path is ever actually energized. We are developing a hierarchical timing simulation system that will use high-level information (at the register-transfer level, for example) to determine the worst-case paths for the defined operations of the system. The values of the worst-case delays will be determined using high-level floorplan information and intra-module timing information. The layout information will allow the simulation system to use transmission line models to estimate communication delays between modules. The use of transmission line models is necessary since the increased circuit switching speeds of GaAs and other technologies result in long interconnections behaving like transmission lines.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] P. Banerjee and J. A. Abraham, "Bounds on algorithm-based fault tolerance in multiple processor systems," *IEEE Trans. Comp.*, vol. C-35, no. 4, pp. 296-306, Apr. 1986. (JSEP)

[2] J. A. Abraham and W. K. Fuchs, "Fault and error models for VLSI" (invited paper), *Proc. IEEE*, vol. 74, no. 5, pp. 639-654, May 1986. (SRC/JSEP)

[3] T. C.-K. Chou and J. A. Abraham, "Distributed control of computer systems," *IEEE Trans. Comp.*, vol. C-35, no. 6, pp. 564-567, June 1986. (JSEP/VHSIC)

[4] M. Malkawi and J. H. Patel. "Performance measurement of paging behavior in multiprogramming systems." *Proc. 13th Int. Symp on Comp Architecture*. Tokyo. Japan. June 1986. pp. 111-118 (JSEP)

[5] P. Banerjee and J. A. Abraham. "Concurrent fault diagnosis in multiple processor systems." *Proc. 16th Int. Symp. on Fault-Tolerant Comp.*. Vienna. Austria. July 1986. pp. 298-303. (JSEP SRC)

[6] P. Banerjee and J. A. Abraham. "Graph theoretic bounds on on-line checks in multiple processor systems." *Proc. National Comp Conf.* New Orleans. LA. Dec. 1986. pp. 283-296. (JSEP)

[7] W. K. Fuchs. K.-L. Wu. and J. A. Abraham. "Comparison and diagnosis of large replicated files." *IEEE Trans. Software Eng.* vol. SE-13. no. 1. pp. 15-22. Jan. 1987. (MCC/JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[8] J. A. Abraham. G. Metze. R. K. Iyer. and J. H. Patel. "The evolution of fault-tolerant computing at the University of Illinois." Chapt. in *Dependable Computing and Fault-Tolerant Systems: The Evolution of Fault-Tolerant Computing. Proceedings of a One-Day Symposium in Honor of William C. Carter* (June 30. 1986. Baden). Avizienis. Kopetz. and Laprie. Eds. New York: Springer-Verlag. 1986. (SRC)

[9] J.-Y. Jou and J. A. Abraham. "Fault-tolerant matrix arithmetic and signal processing on highly concurrent computing structures." *Proc. IEEE (Special Issue on Fault Tolerance in VLSI)*. vol. 74. no. 5. pp. 732-741. May 1986. (SRC)

[10] S. Patel and J. H. Patel. "Effectiveness of heuristics measures for a automatic test pattern generation." *Proc. ACM/IEEE 23rd Design Automation Conf.*. Las Vegas. NV. July 1986. pp. 547-552. (IBM/SRC)

[11] H.-C. Shih and J. A. Abraham. "Transistor-level test generation for physical failures in CMOS circuits." *Proc. ACM/IEEE 23rd Design Automation Conf.*. Las Vegas. NV. July 1986. pp. 243-249. (SRC)

[12] H.-C. Shih and J. A. Abraham. "Fault collapsing techniques for MOS VLSI circuits." *Proc. 16th Int Symp. on Fault-Tolerant Computing*. Vienna. Austria. July 1986. pp. 370-375. (SRC)

[13] C.-Y. Chen and J. A. Abraham. "Fault-tolerant systems for the computation of eigenvalues and singular values" (invited paper). *Proc. SPIE 30th Ann. Int. Technical Symp. on Optical and Optoelectronics Applied Sci. and Eng.* San Diego. CA. vol. 696. Aug. 1986. pp. 228-237. (SRC)

[14] H.-P. Chang. W. A. Rogers. and J. A. Abraham. "Structured functional-level test generation using binary decision diagrams." *Proc. Int. Test Conf.*. Washington. DC. Sept. 1986. pp. 97-104. (SRC/GE)

[15] R. Fujii and J. A. Abraham. "Approaches to circuit-level design for testability." *Proc. Int. Test Conf.*. Washington. DC. Sept. 1986. pp. 480-483. (SRC/DEC)

[16] H.-C. Shih, J. Rahmeh, and J. A. Abraham, "FAUST: an MOS fault simulator with timing information," *IEEE Trans. Computer-Aided Design*, vol. CAD-5, no. 4, pp. 557-563, Oct. 1986. (SRC)

[17] J. A. Abraham, "Research in reliable VLSI architectures at the University of Illinois" (invited paper), *Proc. ACM/IEEE Fall Joint Comp. Conf.*, Dallas, TX, Nov. 1986, pp. 890-893. (SRC)

[18] C.-Y. Chen and J. A. Abraham, "On the design of fault-tolerant systolic arrays with linear cells," *Proc. ACM/IEEE Fall Joint Computer Conf.*, Dallas, TX, Nov. 1986, pp. 400-409. (SRC)

[19] K. A. Hua and J. A. Abraham, "Design of systems with concurrent error detection using software redundancy," *Proc. ACM/IEEE Fall Joint Computer Conf.*, Dallas, TX, Nov. 1986, pp. 826-835. (IBM SRC)

[20] A. Chatterjee and J. A. Abraham, "C-testability for generalized tree structures with applications to Wallace trees and other circuits," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1986, pp. 288-291. (SRC)

[21] J. F. Guzolek, W. A. Rogers, and J. A. Abraham, "WRAP: An algorithm for hierarchical compression of fault simulation primitives," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1986, pp. 338-341. (SRC/Tektronix)

[22] W. A. Rogers and J. A. Abraham, "A performance model for concurrent hierarchical fault simulation," *Proc. Int. Conf. on Computer-Aided Design*, Santa Clara, CA, Nov. 1986, pp. 342-345. (SRC)

[23] P. Banerjee and J. A. Abraham, "A probabilistic model of algorithm-based fault tolerance in array processors for real-time systems," *Proc. Real-Time Syst. Symp.*, New Orleans, LA, Dec. 1986, pp. 72-78. (SRC)

WORK UNIT NUMBER 14

TITLE: New Directions in Fault-Tolerant Computing

SENIOR PRINCIPAL INVESTIGATORS:

P. Banerjee, Research Assistant Professor
K. Fuchs, Research Assistant Professor
R. Iyer, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

H. T. Ho, Research Assistant
S. Hsueh, Research Assistant
C. C. Li, Research Assistant

SCIENTIFIC OBJECTIVE:

This unit is concerned with exploring new directions in fault tolerant computing that will be useful in understanding the basic principles in design, testing, error prediction and circumvention for reliable complex computer systems. Basic research is being performed in the three areas of parallel test pattern generation, reliable distributed database systems for real-time applications, and intelligent error prediction and circumvention.

SUMMARY OF RESEARCH:

Parallel Algorithms for Automatic Test Generation

Our initial investigations into the design of parallel algorithms for automatic test pattern generation on multiprocessor systems have shown a lot of promise. We have identified some techniques for possible parallelization which we are going to implement and evaluate in the future. (1) Partitioning a large circuit into blocks which are assigned to different processors. (2) Performing forward implications in parallel by guessing signal values on lines based on heuristics; the correctness of the guessed values are checked by interprocessor messages. (3) Using multiple backtrace procedures to trace signal determination backwards on multiple paths. (4) Performing D-drive through all the gates of D-frontier simultaneously.

Reliable Distributed Database Systems

Research concerning concurrent detection and recovery of structure and semantic errors in database systems has resulted in a virtual backpointer approach for the on-line detection of errors in linked data structures. Both Virtual Double-Linked Lists and B-trees with Virtual Backpointers have been developed based on the virtual backpointer concept. The data structures are appropriate for real-time applications since they allow concurrent error detection in O(1) time with little or no storage overhead and few extra node accesses. For purposes of analysis, checking window and lock and key concepts have also been introduced. These techniques have been implemented in a data structure software package and are currently undergoing analysis. The implementations are being investigated for performance as well as reliability attributes in both shared memory multiprocessor and distributed work-station environments.

Intelligent Error Prediction and Circumvention

A methodology of model development from the raw error-data to the estimation of cumulative reward has been developed. The results provide an understanding of the different types of errors and recovery processes. The measured data show that the holding times in key operational and failure states are not simple exponential and that a semi-Markov process is necessary to model the system behavior. A sensitivity analysis has also been performed to investigate the significance of using a semi-Markov process (as opposed to a Markov process) to model the measured system. Results show that the Markov process frequently overestimates the error probabilities and underestimates the second moment of the first passage time to the error states.

Based on the model methodology, a measurement-based performability model has been developed. A reward rate is used, which is defined as a function of service rate and the error rate in each state, to estimate the performability of the system and, to depict the cost of different error types and recovery procedures. Results show that not recovering from software errors degrades system effectiveness considerably compared with the effect of not recovering from disk errors if we assume the system continues to provide service in a degraded mode. However, if we assume that both software and disk errors, result in system failed then the effect due to the disk errors is more severe than that due to the software errors. A software reliability model has also been built based on the low-level error data from the MVS operating system running on an IBM 3081 machine. The semi-Markov model developed provides a quantification of system failure characteristics and the interaction between different types of errors.

JSEP-SPONSORED PUBLICATIONS

[1] P Banerjee and J A. Abraham. "Bounds on algorithm-based fault tolerance in multiple processor systems" *IEEE Trans Comput.*, vol. C-35, no. 4, Apr. 1986, pp. 296-306.

[2] P. Banerjee and J. A. Abraham. "Graph-theoretic bounds on on-line checks in multiple processor systems." *AFIPS Proc. National Comput Conf.*, Las Vegas, Nevada, Jun. 1986.

[3] P. Banerjee and J. A. Abraham. "Concurrent fault diagnosis in multiple processor systems." *Proc. 16th Fault Tolerant Computing Symp.*, Vienna, Austria, July 1986.

[4] W. K. Fuchs. "A specification-based approach to concurrent structure verification in multiprocessor systems." *IEEE Int. Conf. on Comput Design*, Oct. 1986, pp. 375-378.

[5] W. K. Fuchs, K. L. Wu, J. A. Abraham. "Comparison and diagnosis of distributed database files." *IEEE Trans. Software Eng.* (Special Issue on Distributed Computing), Jan. 1987, pp. 15-22.

[6] M. Sharma, W. K. Fuchs. "Applicative environments for reliable multiprocessor systems," to appear: *1987 Princeton Workshop on Algorithm, Architecture and Technology Issues in Models of Concurrent Computation*, Sept. 1987.

[7] M. C. Hsueh, R. K. Iyer and K. S. Trivedi, "A measurement-based performability a model for multiprocessor system," in *2nd Int. Workshop on Applied Mathematics and Performance Reliability Models of Computer Communications Systems*, (Rome, Italy, May 25-29, 1987) (to appear).

[8] P McGuire and R. K. Iyer, " A measurement-based study of concurrency in a multiprocessor," in *1987 Int Conf. on Parallel Processing*, St. Charles, IL, Aug. 17-21, 1987 (to appear).

[9] M. C. Hsueh and R. K. Iyer, "Measurement-based model of software reliability in a production environment," in *Proc. Comput. Software and Applications Conf.*, Tokyo, Japan, Oct. 5-9, 1987 (to appear).

WORK UNIT NUMBER 15

TITLE: Efficient Computation Techniques

SENIOR PRINCIPAL INVESTIGATORS:

D. J. Brown, Research Associate Professor
M. C. Loui, Research Associate Professor
F. P. Preparata, Research Professor
V. L. Ramachandran, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

A. Kanevsky, Research Assistant
M. L. Prastein, Research Assistant
R. Tamassia, Research Assistant
I. Tollis, Research Assistant
J. L. Trahan, Research Assistant

SCIENTIFIC OBJECTIVE:

The analysis and the design of efficient computation techniques has been for several years one of the most vigorous areas of research in information processing. Its impact has been not only on the availability of better computational methods for a number of significant applications, but also on the awareness in the computing community of the crucial importance of algorithmic design. By investigating both upper and lower bounds to the resource requirements of specific applications, this discipline effectively develops a methodology aiming at a quantitative formulation of the inherent difficulty of problems in the appropriate computation models.

The involvement of our research group with this topic is well established and dates back to the early seventies. Our record over this period shows that our focus (as well as that of our peer community) has been adjusting dynamically, as changes in technologies have modified the general research horizon and the perception of relevance. The most significant change of this type has been the advent of Very-Large-Scale-Integration (VLSI), which has profoundly influenced essentially every facet of our current research interests. The advent of VLSI is important in two major respects: one is the present possibility to realize massively parallel computers, the other is the introduction of criteria of complexity (the VLSI "model") which take into account the design rules dictated by the new technology. Therefore, while maintaining our interest for problems in the more traditional areas (Von Neumann computations), our current work emphasizes research on the potentially revolutionary domain of concurrent computation.

SUMMARY OF RESEARCH:

Parallel Computation and Graph Algorithms

In parallel computation, we have been looking at fast parallel algorithms for combinatorial problems. We have developed a fast parallel algorithm for the linear programming problem with two variables per inequality and two variables in the optimization function. The parallel algorithm runs in polylog time with a subexponential number of processors.

In continuation of our work on graph algorithms, we have designed several parallel NC algorithms for reducible flow graphs. We have NC algorithms for recognizing rfg's, for finding a depth first search tree in an rfg, and for finding a minimum feedback vertex set. We have also developed an RNC algorithm for finding a minimum weight feedback arc set in arc-weighted rfg's.

Vertex connectivity is an important graph property. We have developed a new algorithm for testing vertex four-connectivity and for finding all separation triplets in a triconnected graph in $O(n^2)$ sequential time, and in $O(\log^2 n)$ parallel time on a CRCW PRAM with $O(n^2)$ processors. This improves previous bounds for the problem for both the sequential and parallel cases.

We have looked into efficient parallel circuits and algorithms for the problem of finding the n-bit result of dividing one n-bit number by another. We have developed a logspace uniform family of circuits for division of depth $D(n)=O((1/\delta^3)\cdot \log n \cdot \log\log n)$ and size $S(n)=O((1/\delta^3)\cdot n^{1+\delta})$, for any $\delta > 0$. This translates into a uniform parallel algorithm on a shared memory machine (PRAM) with bit operations and exclusive memory writes with parallel time $D(n)$ using $O(S(n))$ processors. It also translates into a parallel algorithm for a concurrent write PRAM with parallel time $O(D(n)/\log\log n)$ using $O(S(n))$ processors. We have also obtained a polynomial-time uniform family of circuits for division of depth $O((1/\delta^2)\cdot \log n)$ and size $O(S(n))$. Finally we have looked to small depth circuits for the evaluation of arithmetic expressions. We have some preliminary results on this problem.

Models of Parallel Computation

The most important model of parallel computation is the *Parallel Random Access Machine* (*PRAM*), which comprises multiple processors that execute instructions synchronously and share a common memory. This model provides the foundation for the design of highly parallel algorithms. Because of the widespread use of this model, an understanding of its capabilities is crucial. The usual *PRAM* model has the following instructions: bitwise boolean operations; integer addition, subtraction, and comparisons with conditional jumps; indirect read and write. We have studied the computational capabilities of deterministic *PRAMs* with additional instructions.

We proved that polynomial space on Turing machines (*PSPACE*) is equivalent to polynomial time on *PRAMs* with unit-time multiplication and on *PRAMs* with unit-time unrestricted left shift and right shift. These results are surprising for two reasons. First, for the *sequential* random access machine running in polynomial time, adding unit-time multiplication or unit-time unrestricted left shift increases its power from *PTIME* to *PSPACE*, whereas adding one of these operations to a *PRAM* does *not* increase its power beyond a polynomial amount. Second, despite the potential speed offered by massive parallelism, a *PRAM* with unit-cost multiplication or unrestricted shifts is at most polynomially faster than a sequential random access machine with the same additional operation.

VLSI Layout

We have developed new algorithms for multilayer channel routing and, moreover, we now have a unified framework in which many previously known results can be obtained. We have considered various models, including: Manhattan, knock-knee, unit vertical overlap, routing with diagonal wires, and unrestricted overlap. In addition, we are investigating the possibility of having "stacked pins." Some lower-bound results have also been obtained.

We have also looked at the question of delay in VLSI layouts and the area penalty caused by making local expansions in layouts. We have obtained tight bounds for these for various types of layouts. In particular, we show that reducing capacitive delay in layouts by introducing drivers can sometimes cause a large area increase.

Complexity of Graph Problems

Recent advances in graph theory and graph algorithms may have profound implications for the field of complexity theory. Work by Robertson and Seymour has provided powerful new tools to show problems in P by proving only the **existence** of polynomial time decision algorithms. We have applied these techniques to show a variety of problems to be polynomial time solvable: some were not previously known even to be decidable, others were known to be in P, but low-order polynomial time solutions were not known. Examples come from such diverse areas as topological embeddings, reliability and fault-tolerance, and VLSI applications, as well as straightforward graph problems. Moreover, a number of the problems are self-reducible: answering the decision question can be used to construct a solution.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] G. Bilardi and F. P. Preparata, "Area-time lower-bound techniques with applications to sorting," *Algorithmica*, vol. 1, pp. 65-91, 1986. (JSEP/NSF)

[2] B. Chazelle, R. Cole, F. P. Preparata, and C. Yap, "New upper bounds for neighbor searching," *Inform. Contr.*, vol. 68, nos. 1-3, pp. 105-124, 1986. (JSEP/NSF/ONR)

[3] E. Gafni, M. C. Loui, P. Tiwari, D. B. West, and S. Zaks, "Lower bounds on common knowledge in distributed algorithms," in *Distributed Algorithms on Graphs: Proc. First Inter Workshop on Distributed Algorithms on Graphs.*, Ottawa, Canada, Aug. 1985, E. Gafni and N. Santoro, Eds. Carleton University Press, 1986, pp. 49-67. (JSEP/NSF/IBM)

[4] R. Tamassia and I. G. Tollis, "Algorithms for visibility representations of planar graphs," in *Lecture Notes in Computer Science, Proc. STACS '86*, vol. 210, Springer Verlag, 1986, pp. 130-141. (JSEP)

[5] R. Tamassia and I. Tollis, "A unified approach to visibility representations of planar graphs," *Discrete and Computational Geometry*, vol. 1, no. 4, pp. 32-341, 1986. (JSEP)

[6] M. C. Loui, T. A. Matsushita, and D. B. West, "Election in a complete network with a sense of direction," *Inform. Process. Lett.*, vol. 22, no. 4, pp. 185-187, Apr. 1986. (JSEP/NSF/Kodak)

[7] G. Leuker, N. Megiddo, and V. Ramachandran, "Linear programming with two variables per inequality in polylog time," in *Proc. 18th Annu. Symp. on Theory of Computing (STOC)*, Berkeley, CA, pp. 196-205, May 1986. (JSEP/NSF/IBM)

[8] M. L. Brady and D. J. Brown, "Three layer channel routing with stacked pins," in *Proc. 24th Ann. Allerton Conf. on Communication, Control, and Computing*, Univ. of Illinois, Oct. 1986. (JSEP)

[9] V. Ramachandran, "On driving many long wires in a VLSI layout," *J. Assoc. Comput. Mach.*, vol. 33, no. 4, pp. 687-701, Oct. 1986. (JSEP)

[10] G. Bilardi and F. P. Preparata, "Size-time complexity of Boolean networks for prefix computations," to be presented at the *19th Ann. ACM Symp. on Theory of Computing (STOC)*, New York, NY, 1987. (JSEP/NSF)

[11] V. Ramachandran. "Fast parallel algorithms for reducible flow graphs." *1987 Princeton Workshop on Algorithm, Architecture and Technology Issues in Models of Concurrent Computation* 1987 (to appear). (JSEP/NSF/SRC)

[12] A. M. Schwartz and M. C. Loui. "Dictionary machines on cube-class networks." *IEEE Trans. Comput.*, vol. C-36, no. 1, pp. 100-105, Jan. 1987. (JSEP)

[13] D. J. Brown, M. R. Fellows, and M. A. Langston. "Some applications of nonconstructive proofs for polynomial-time decidability." *The Southeastern Int. Conf. on Combinatorics, Graph Theory, and Computing*, Ft. Lauderdale, FL, Feb. 1987. (JSEP/NSF)

[14] D. J. Brown, M. R. Fellows, and M. A. Langston. "Nonconstructive tools for guaranteeing polynomial time complexity." *Princeton Forum on Algorithms and Complexity*, Mar. 1987. (JSEP/NSF)

[15] M. C. Loui and H. H. Abu Amara. "Memory requirements for agreement among unreliable asynchronous processes." *Advances in Computing Research*, vol. 4, 1987 (to appear). (JSEP/ONR/Kodak)

[16] M. L. Prastein. "Precedence-constrained scheduling with minimum time and communication." *Proc. 21st Annu. Conf. on Inform. Sci. and Syst.*, Baltimore, MD, Mar. 25-27, 1987 (to appear). (ONR/JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[17] C. Batini, P. Brunetti, G. Di Battista, P. Naggar, E. Nardelli, G. Richelli, and R. Tamassia. "An automatic layout facility and its applications." in *Proc. Int. Workshop on Software Eng. Environment*, Beijing, 1986 (invited).

[18] C. Batini, E. Nardelli, and R. Tamassia. "A layout algorithm for data-flow diagrams." *IEEE Trans. Software Eng.*, vol. SE-12, no. 4, pp. 538-546, 1986.

[19] G. Di Battista and R. Tamassia. "An integrated graphic system for designing and accessing statistical data bases." in *Proc. 7th Symp. on Computational Statistics (COMPSTAT 1986)*, Rome, 1986.

[20] K. Mehlhorn, F. P. Preparata, and M. Sarrafzadeh. "Channel routing in knock-knee mode: Simplified algorithms and proofs." *Algorithmica*, vol. 1, pp. 213-221, 1986. (SRC)

[21] G. Miller, V. Ramachandran, and E. Kaltofen. "Efficient parallel evaluation of straight-line code." *VLSI Algorithms and Architectures*, Springer-Verlag Lecture Notes in Computer Science 227, 1986, pp. 236-245. (NSF/SRC/IBM)

[22] V. Ramachandran. "Single residue error correction in residue number systems." in *Residue Number System Arithmetic -- Modern Applications in Digital Signal Processing*, M. A. Soderstrand, W. K. Jenkins, G. A. Jullien, and F. J. Taylor, Eds. New York: IEEE Press, 1986, pp. 361-364.

[23] M. L. Brody and D. J. Brown. "Optimal multilayer channel routing with overlap." in *Proc. 1986 MIT Conf. on Advanced Research in VLSI*, Cambridge, MA, Apr. 1986, pp. 281-296.

[24] S. R. Maddila, "Decomposition algorithm for moving a ladder among rectangular obstacles," in *Proc. IEEE Int. Conf. on Robotics and Automation*, San Francisco, CA, Apr. 1986, pp. 1413-1418. (NSF)

[25] V. Ramachandran, "Algorithmic aspects of MOS VLSI switch-level simulation with race detection," *IEEE Trans. Computers*, vol. C-35, no. 5, pp. 462-475, May 1986. (NSF)

[26] H. Alt, T. Hagerup, K. Mehlhorn, and F. P. Preparata, "Graph-theoretic problems in the memory organization of distributed systems," in *12th Int. Workshop on Graphtheoretic Concepts in Computer Science*, June 1986.

[27] S. R. Maddila and C. K. Yap, "Moving a polygon around the corner in a corridor," in *Proc. 2nd Ann. Symp. on Computational Geometry*, Yorktown Ht., NY, June 1986, pp. 187-192. (NSF)

[28] J. O'Rourke, S. R. Maddila, and A. Aggarwal, "An optimal algorithm for finding minimal enclosing triangles," *J. Algorithms*, vol. 7, no. 2, pp. 258-269, June 1986. (NSF)

[29] R. Tamassia and I. Tollis, "Centipede graphs and visibility on a cylinder," in *12th Int. Workshop on Graphtheoretic Concepts in Computer Science*, June 1986. (NSF)

[30] H. Alt, T. Hagerup, K. Mehlhorn, and F. P. Preparata, "Deterministic simulation of idealized parallel computers on more realistic ones," *Mathematical Foundations of Computer Science*, Bratislava, Czechoslovakia, Aug. 1986. (NSF)

[31] B. Krishnamurthy and I. G. Tollis, "Improved techniques for estimating signal probabilities," in *Proc. Int. Test Conf. 1986 (ITS '86)*, Washington, D.C., Sept. 1986, pp. 244-251.

[32] S. Hornick and M. Sarrafzadeh, "On problem transformability in VLSI," *Algorithmica*, vol. 2, no. 1, pp. 97-111, 1987. (SRC)

[33] G. Miller and V. Ramachandran, "A new graph triconnectivity algorithm and its parallelization," in *Proc. 19th Ann. ACM Symp. on Theory of Computing (STOC)*, New York, NY, 1987. (NSF/SRC)

[34] R. Tamassia and I. G. Tollis, "Efficient embedding of planar graphs in linear time," in *Proc. IEEE Int. Symp. on Circuits and Syst.*, Philadelphia, PA, 1987, pp. 495-498. (SRC)

[35] M. L. Brady and M. Sarrafzadeh, "Layout stretching to insure wirability," in *Proc. 21st Ann. Conf. on Inform. Sci. and Syst.*, Johns Hopkins Univ., Baltimore, MD, Mar. 1987.

[36] M. Ben-Or, E. Feig, D. Kozen, and P. Tiwari, "A fast parallel algorithm for determining all roots of a polynomial with real roots," *SIAM J. Comput.* (to appear). (IBM/ONR)

[37] G. Bilardi and M. Sarrafzadeh, "Optimal VLSI circuits for discrete Fourier transform," *Advances in Computing Research* (to appear). (SRC/NSF IBM)

[38] P. Czerwinski and V. Ramachandran, "Optimal VLSI graph embeddings in variable aspect ratio rectangles," *Algorithmica* (to appear). (SRC/IBM)

[39] A. S. Hodel and M. C. Loui, "Optimal dynamic embedding of X-trees into arrays," *Theoretical Computer Science* (to appear). (Kodak)

[40] K. Mehlhorn and F. P. Preparata, "Area-time optimal division for $T = \Omega((\log n)^{1+\epsilon})$," *Inform and Computation* (to appear). (NSF)

[41] P. A. Peterson and M. C. Loui, "The general maximum matching algorithm of Micali and Vazirani," *Algorithmica* (to appear). (ONR)

[42] V. Ramachandran, "The complexity of minimum cut and maximum flow problems in an acyclic network," *Networks* (to appear). (NSF IBM)

[43] M. Sarrafzadeh, "On the complexity of the channel routing problem in the knock-knee model," *IEEE Trans. CAD* (to appear). (SRC)

[44] R. Tamassia, "On embedding a graph in the grid with the minimum number of bends," *SIAM J. on Comput.*, vol. 16, no. 3, 1987 (to appear).

[45] P. Tiwari and M. C. Loui, "Simulation of chaotic algorithms by token algorithms," in *Distributed Algorithms on Graphs: Proc. First Intern. Workshop on Distributed Algorithms on Graphs*, Ottawa, Canada, Aug. 1985, E. Gafni and N. Santoro, Eds. Carleton University Press, 1986, pp. 143-152. (ONR)

WORK UNIT NUMBER 16

TITLE: High-Resolution Sensor Array Processing

SENIOR PRINCIPAL INVESTIGATORS:

T. S. Huang, Research Professor
W. K. Jenkins, Research Professor
D. C. Munson, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. Blostein, Research Assistant
H. H. Chen, Research Assistant
G. Kakazu, Research Assistant
J. J. Murphy, Teaching Assistant

SCIENTIFIC OBJECTIVE:

The term "sensor array system" refers to a large class of remote sensing systems in which data are collected and recorded by many independent sensors, or by one sensor that is moved to different spatial positions. The recorded data are processed by a digital array algorithm to produce a high-resolution object function. Some of the more important multi-sensor array systems now in use are synthetic aperture radar (SAR), computer-aided tomography (CAT), and beam-forming sonar. The objective of the research in this unit is to develop both the theory and computer verification of new signal processing methods with the goal of overcoming current limits on resolution and data throughput rates for these systems. Specifically, we propose to develop reconstruction algorithms that: (1) can achieve high resolution from a limited amount of sampled data; (2) have small enough computational complexities that real-time implementation is feasible; and (3) can be partitioned into sets of elementary operations suitable for VLSI realization.

SUMMARY OF RESEARCH:

During the past year our JSEP research has concentrated on two aspects of high-resolution sensor array processing: adaptive filtering and beamforming algorithms, and reconstruction algorithms for synthetic aperture radar (SAR). In the adaptive area we have continued studying discrete orthogonal transforms for improving convergence properties in adaptive finite impulse response (FIR) digital filters which operate in colored noise environments. Also, we have transferred some of our results to the problem of adaptive beamforming and have shown that the concept of prewhitening by means of applying an orthogonal transformation can improve convergence properties of adaptive beamformers. Related to SAR, we have developed a fast Hankel transform algorithm for accurately inverting polar-format SAR data; and we have analyzed the spatial domain effects of the Fourier domain polar-to-Cartesian interpolation utilized in spotlight mode SAR. We have also examined the possibilities of artificially extending (extrapolating) the known Fourier data for improved resolution and of reconstructing from just the phase of the Fourier data to simplify computation.

Adaptive Filtering and Beamforming

After having achieved significant improvements in FIR digital filters with the Walsh-Hadamard transform (WHT) [2], we designed a new orthogonal transform called the Power-of-Two (PO2) transform that has a similar structure to the WHT but which has real-valued coefficients that are simple powers-of-2 [13]. Since the PO2 transform is a generalization of the WHT, it was expected that it would achieve faster convergence rates while requiring only shifts and adds for implementation; this expected improvement was demonstrated in numerous computer experiments. It was recently shown that the discrete Hartley transform (DHT), which is a close relative of the FFT, preforms better than any of the FFT, WHT, or PO2 transforms and is perhaps the strongest candidate for real-time adaptive filtering applications.

In broadband beamforming, each sensor in the array is typically followed by an FIR digital filter to provide the necessary frequency-dependent array weighting, and the weights can be adjusted adaptively to steer the nulls of the beampattern toward any desired sources. For adaptive beamformers based on the LMS algorithm in a multi-signal environment, convergence is data dependent and is characterized by highly disparate modes, resulting in slow and noisy adaptation. Recently, we began to examine the feasibility of using orthogonal transforms (discussed above for adaptive filtering) for the multichannel wideband beamforming problem to improve convergence properties of an adaptive beamformer. A special class of beamformers, the generalized sidelobe canceller, was studied. This structure converts the problem of linearly constrained adaptive beamforming to one of unconstrained multiple reference noise cancelling. Applying orthogonal transforms to this multiple input case is nontrivial, since many different orderings of the input data vectors are possible prior to transformation. Overall, it was demonstrated by computer experiments that improved convergence rates can be achieved using fixed (time-invariant) orthogonal transforms, but performance is highly dependent upon input data and the array processing structure. The desired result of identifying a single transform that works well for a broad class of input signals and different numbers of sensors has not yet been accomplished. Further research is needed to develop criteria for choosing a good transform from among the many possible choices, for ordering the data vectors that are presented as inputs to the transform algorithm, and for evaluating the results on an analytical basis.

SAR Reconstruction Algorithms

We have obtained several interesting and useful results on algorithms for SAR image reconstruction. In spotlight mode SAR, preliminary processing of the raw data provides samples of the Fourier transform of the terrain or scene reflectivity. Unfortunately, these samples are available on a polar grid in only a very small region of Fourier space. One scheme to invert the Fourier data is to first interpolate to a Cartesian grid and to then apply a 2-D FFT. In [8] we studied the effect of imperfect Fourier domain interpolation and showed that serious artifacts may arise in the spatial domain. Both the locations and amplitudes of these artifacts can be predicted. In [1] we considered the possibility of extrapolating the Fourier data, to increase resolution, prior to inversion. It was shown that conventional extrapolation algorithms will yield increased resolution only if the width of the known Fourier data is less than the bandwidth of just the magnitude of the scene reflectivity. Publication [3] shows that for scenes of high contrast, a high quality SAR image can be produced from just the phase of the Fourier data, offering the possibility of considerably reduced computation. Finally, in [9] a new algorithm was developed for efficiently computing a series of Hankel transforms. This algorithm was subsequently applied in a Hankel transform-based algorithm for inverting polar Fourier data in a highly accurate manner. Indications are that the Hankel transform approach is very competitive in terms of quality and computational cost with the more well-known convolution-back-projection algorithm.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] D. C. Munson, Jr. and E. A. Ullman, "Support-limited extrapolation of offset Fourier data," *Proc. 1986 Int. Conf. on Acoustics, Speech, and Signal Process.*, Tokyo, Japan, pp. 2483-2486, Apr. 7-11, 1986. (JSEP)

[2] J. Kreidle and W. K. Jenkins, "Adaptive digital filters using the Walsh-Hadamard Transform," *Proc. Int. Symp. on Circuits and Syst.*, San Jose, CA, pp. 875-878, May 1986. (JSEP)

[3] D. C. Munson, Jr. and J. L. C. Sanz, "Phase-only image reconstruction from offset Fourier data," *Optical Eng.*, vol. 25, pp. 655-661, May 1986. (JSEP/IBM Corp.)

[4] W. K. Jenkins and M. D. Desai, "The discrete-frequency Fourier transform," *IEEE Trans. Circuits and Syst.*, vol. CAS-23, no. 7, pp. 732-733, July 1986. (JSEP)

[5] A. C. Bovik, T. S. Huang, and D. C. Munson, Jr., "Nonparametric tests for edge detection in noise," *Patt. Recog.*, vol. 19, no. 3, pp. 209-219, 1986. (JSEP)

[6] M. A. Soderstrand, J. K. Jenkins, G. A. Jullien, and F. J. Taylor (eds.), *Modern Applications of Residue Number System Arithmetic to Digital Signal Processing*. New York: IEEE Press, 1986. (JSEP/NSF)

[7] H. Fan and W. K. Jenkins, "A new adaptive digital filter," *IEEE Trans. Circuits and Syst.*, vol. CAS-23, no. 10, pp. 939-947, Oct. 1986. (JSEP/AT&T)

[8] D. C. Munson, Jr. and J. D. O'Brien, "An analysis of artifacts due to Fourier domain interpolation," *Proc. Twentieth Ann. Asilomar Conf. on Signals, Syst., and Comput.*, Pacific Grove, CA, Nov. 10-12, 1986. (JSEP/AFWAL)

[9] W. E. Higgins and D. C. Munson, Jr., "An algorithm for computing general integer-order Hankel transforms," *IEEE Trans. Acoustics, Speech, and Signal Process.*, vol. ASSP-35, pp. 86-97, Jan. 1987. (JSEP)

[10] A. C. Bovik, T. S. Huang, and D. C. Munson, Jr., "The effect of median filtering on edge estimation and detection," *IEEE Trans. Pattern Anal. and Machine Intell.*, vol. PAMI-9, pp. 181-194, Mar. 1987. (JSEP)

[11] W. E. Higgins and D. C. Munson, Jr., "Tomographic image reconstruction via the Hankel transform reconstruction algorithm," to appear in *IEEE Trans. Medical Imaging*. (JSEP)

[12] W. K. Jenkins, "Analog signal processing," in *The Encyclopedia of Physical Science and Technology*, Robert A. Meyers, Ed., Academic Press, Inc. (to appear). (JSEP)

[13] W. K. Jenkins and D. F. Marshall, "On the analysis and design of unitary transformations for adaptive FIR digital filters," *Proc. 29th Midwest Symp. on Circuits and Syst.*, Lincoln, NB, Aug. 1986 (invited) (to appear). (JSEP/AT&T).

[14] W. K. Jenkins, D. F. Marshall, J. R. Kreidle, and J. J. Murphy, "The use of orthogonal transformations for improving performance of adaptive filters," to appear in *IEEE Trans. Circuits and Syst.*, Special Issue on Adaptive Systems and Applications. (JSEP/AT&T)

[15] W. K. Jenkins and J. D. O'Brien, "The design of optimal 2-dimensional windows for support regions with irregular shape," *Proc. 1986 Asilomar Conf. on Signals, Syst., and Comput.*, Pacific Grove, CA, Nov. 1986 (invited) (to appear). (JSEP)

[16] M. Nayeri, D. F. Marshall, and W. K. Jenkins, "Relationships between error surfaces and adaptive architectures in adaptive filters," in *Proc. Int. Symp. on Circuits and Syst.*, Philadelphia, PA, May 1987 (invited) (to appear). (JSEP/AT&T)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[17] W. K. Jenkins and M. Nayeri, "Adaptive filters realized with second order sections," *Proc. Int. Conf. on Acoustics, Speech, and Signal Process.*, Tokyo, Japan, pp. 2103-2105, Apr. 1986. (AT&T)

[18] W. K. Jenkins, M. Nayeri, and H. Fan, "New algorithms for IIR adaptive filtering," *Symp. Digest of the Fifth Kobe Int. Symp. on Electronics and Inform. Sci.*, Kobe, Japan, pp. 3-1 to 3-11, Apr. 1986 (Invited). (AT&T)

[19] E. J. Diethorn and D. C. Munson, Jr., "Finite word length FIR digital filter design using simulated annealing," *Proc. 1986 IEEE Int. Symp. on Circuits and Syst.*, San Jose, CA, pp. 217-220, May 5-7, 1986. (NSF)

[20] H. Fan and W. K. Jenkins, "A family of adaptive IIR digital filtering algorithms with global convergence," *Proc. Int. Symp. on Circuits and Syst.*, San Jose, CA, pp. 221-224, May 1986. (AT&T)

[21] A. C. Bovik and D. C. Munson, Jr., "Edge detection using median comparisons," *Computer Vision, Graphics, and Image Process.*, vol. 33, pp. 377-389, 1986. (U. of Texas)

[22] D. C. Munson, Jr., "Linear time-varying signal processing--Analysis, design, and applications," *Proc. 1986 Digital Signal Process. Workshop*, Chatham, MA, pp. 2.1.1-2.1.2, Oct. 1986. (NSF)

[23] A. C. Bovik and D. C. Munson, Jr., "Optimal detection of object boundaries in uncorrelated speckle," *Optical Eng.*, vol. 25, pp. 1246-1252, Nov. 1986. (U. of Texas)

WORK UNIT NUMBER 17

TITLE: Parallel VLSI Structures for Sensor Array Processing

SENIOR PRINCIPAL INVESTIGATORS:

K. S. Arun, Research Assistant Professor
W. K. Jenkins, Research Professor
B. W. Wah, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

M. Aboelaze, Research Assistant
K. Baumgartner, Research Assistant
M. Gooley, Research Assistant
J. V. Krogmeier, Research Assistant
G. J. Li, Research Assistant
V. Saletore, Research Assistant

SCIENTIFIC OBJECTIVE:

To develop high throughput, parallel VLSI structures for the real-time implementation of high-resolution algorithms required in sensor array systems such as synthetic aperture radars, beamforming sonars, direction finders, x-ray cat scanners, and acoustic and NMR imaging systems.

SUMMARY OF RESEARCH:

Research on this new JSEP unit, which began on October 1, 1986, has concentrated on high-throughput multiprocessor VLSI structures for some common linear, shift-invariant signal processing kernels such as FIR and IIR digital filtering, on systematic design methodologies for mapping signal processing algorithms into regular and modular VLSI structures, and on studying the use of residue number system (RNS) arithmetic for designing a fault-tolerant arithmetic cell to be used as a standard cell in the design of VLSI sensor array processors.

We have designed ultra-fast structures for low-order digital filters, using a large number of processors to generate multiple outputs per multiplication cycle (which can be as small as a clock cycle). These structures can have throughput rates many times higher than the clock frequency on the chip. Earlier, we had reported work on modified conventional direct-form FIR and IIR filter structures for high-throughput VLSI implementation [1]. Since this unit began in October 1986, we have also obtained alternate high-throughput filter structures by modifying other conventional filter structures such as the cascade and parallel forms. It is expected that these alternate structures will be less sensitive to finite-precision errors. These new structures use the same number of processors as the modified direct form structures of [1], for a given filter order and a given throughput rate. Conventional parallel and cascade forms are well known to have superior finite-precision behavior, compared to the conventional direct forms ("conventional" refers to structures that produce one output per multiplication cycle). We will demonstrate that the same properties hold for the new high-throughput structures. Although none of the new high-throughput structures achieve 100% processor utilization in the IIR case, they all achieve 100% utilization for the FIR application. In both cases, the processor utilization factor is higher than that achieved by the general state-space structures that have received wide attention in the literature.

During the past year we continued our study of systematic design methodologies to map algorithms into regular modular structures. We have studied the complexities in volume and wire length of mapping problems in two and three dimensions [4,6], studied the design of macropipeline of systolic arrays [8], and investigated the mapping of dynamic programming algorithms into systolic arrays [5]. We have also continued to study the application of RNS arithmetic to designing VLSI modules that can be used for high-resolution sensor array processing [2,7,11,12]. A semi-custom integrated circuit module was designed for an RNS digital filter of order 8 using the IBM MVISA CAD system that is located on the campus of the University of Illinois [13]. (Note that this work was done largely before unit 17 began, and is now continuing under this sponsorship.) A programmable 4-bit module was designed using finite field logarithm addition to completely eliminate multipliers on the chip. The chip design was done with MVISA, which then was used to simulate the hardware operation and estimate physical parameters. MVISA estimates that the 4.2 mm chip consumes 89 mW and operates at a system cycle frequency of 10 mHz, which corresponds to a data-cycle frequency of 1.2 mHz. The design used 529 out of a possible 560 available cells. The chip was recently fabricated at the IBM Manassas facility and is now undergoing testing and verification.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] K. S. Arun, "Ultra-high-speed parallel implementation of low-order digital filters," *Proc. 1986 IEEE Int. Symp. on Circuits and Syst.*, San Jose, CA, May 1986, pp. 944-946. (JSEP)

[2] S. F. Lao, "VLSI implementation of a residue number digital filter," Department of Electrical and Computer Engineering, University of Illinois, 1986. (JSEP)

[3] M. Aboelaze and B. W. Wah, "Complexities of layouts in three-dimensional VLSI circuits," CSL Technical Report CSG-63, Coordinated Science Laboratory, University of Illinois, Jan. 1987. (JSEP/NSF)

[4] K. S. Seijko, "Adaptive beamforming with the transform domain LMS algorithm," Technical Report UILU-ENG-87-2214, Coordinated Science Laboratory, University of Illinois, Feb. 1987. (JSEP)

[5] W. K. Jenkins and J. V. Krogmeier, "The design of dual-mode complex signal processors based on quadratic modular number codes," *IEEE Trans. Circuits and Syst.*, Special Issue on Complex Signal Processing, vol. CAS-34, no. 4, pp. 359-364, Apr. 1987. (JSEP)

[6] M. Aboelaze and B. W. Wah, "Complexities of layouts in three-dimensional VLSI circuits," in *Proc. Int. Symp. on Circuits and Syst.*, May 1987 (invited) (to appear). (JSEP/NSF)

[7] W. K. Jenkins and S. F. Lao, "The design of an RNS digital filter module using the IBM MVISA VLSI design system," in *Proc. Int. Symp. on Circuits and Syst.*, Philadelphia, PA, May 1987, pp. 126-129 (invited). (JSEP)

[8] B. W. Wah and G.-J. Li, "Systolic processing for dynamic programming problems," invited paper to appear in special issue on array processing, *Circuits, Systems, and Signal Processing*, 1987. (JSEP/NSF)

[9] B. W. Wah, M. Aboelaze, and W.-J. Shang, "Buffering in macropipelines of systolic arrays," to appear in *J. Parallel and Distributed Comput.* (JSEP/NSF)

[10] W. K. Jenkins, "Finite arithmetic concepts," in *Handbook on Digital Signal Processing*, J. F. Kaiser and S. K. Mitra, Eds. Van Nostrum Book Co. (to appear). (JSEP/NSF)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[11] K. S. Arun, "Ultra-high-speed parallel implementation of low-order digital filters," *Proc. Int. Symp. on Circuits and Syst.*, San Jose, CA, pp. 944-946, May 1986. (University of Illinois)

[12] W. K. Jenkins, and J. V. Krogmeier, "Complex digital filtering in quadratic modular number systems," *Proc. Int. Symp. on Circuits and Syst.*, San Jose, CA, pp. 1117-1120, May 1986 (invited). (NSF)

[13] W. K. Jenkins and D. F. Marshall, "Number theoretic architectures for adaptive digital filters," *Proc. 1986 Asilomar Conf. on Signals, Syst., and Comput.*, Pacific Grove, CA, Nov. 1986, to appear (invited). (NSF/AT&T)

[14] W. K. Jenkins and E. J. Altman, "Self-checking properties of residue number error checkers based on mixed radix conversions," to appear in *IEEE Trans. Circuits and Syst.* (ARO/NSF)

WORK UNIT NUMBER 18

TITLE: Adaptive Algorithms for Identification, Filtering, Control, and Signal Processing

SENIOR PRINCIPAL INVESTIGATORS:

P. V. Kokotovic, Research Professor
P. R. Kumar, Research Associate Professor
J. V. Medanic, Visiting Research Professor
W. R. Perkins, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

S. T. Hung, Research Assistant
D. Rhode, Research Assistant
J. Schiano, Research Assistant
D.Schoenwald, Research Assistant
H. S. Tharp, Research Assistant
C. Tseng, Research Assistant

SCIENTIFIC OBJECTIVE:

Our group has been and is in the forefront of research on a wide array of problems in adaptive systems; some of the problem formulations, methods and results which have originated in our research group have been accepted by leading researchers worldwide and are being experimentally tested. This accumulated experience and knowledge in the field puts us in the best position to address the underlying fundamental issues and to develop a theory for adaptive algorithms which operate in partially modeled environments.

Our approach embodies the philosophy that adaptive systems, be they adaptive filters, estimators and controllers, or diagnostic and tuning software for automatic quality control and maintenance, are logical on-line extensions of well-tested off-line algorithms, and as such, should inherit their robustness properties. To achieve this level of realism, we allow our convergence and stability conditions to be signal-dependent, and guarantee them in the domain of interest, rather than globally. This closes the gap separating the realistic conditions from the mathematically appealing global results derived under unrealistic and unverifiable modeling assumptions. The robustness properties guaranteed by our approach will compensate for the loss of fictitious globality.

Toward this general objective, one of our goals in this research project is to investigate the key question of whether there are *self-tuning* algorithms with the important feature that the algorithm will automatically tune itself to a correct regulator for a given unknown system. Earlier versions of such algorithms have had a big impact on the practical control of a certain class of systems, and are also beginning to be fabricated on chips and installed in industrial plants, vehicles, ships, and other communication and control equipment.

Our second goal is to examine the behavior of the algorithms in a variety of environments where precise modeling assumptions are violated. Following the first encouraging results, one of our objectives is to develop a methodology to design algorithms which are capable of using the available *a priori* information about systems to be identified, estimated and/or controlled, and to avoid limitations imposed by preselected parameterizations. We instead plan to use existing physical parameters and thus enhance not only robustness, but also serviceability of the control instrumentation.

SUMMARY OF RESEARCH:

The frequency-weighted projective controls methodology will be extended to include disturbance rejection as well as robustness to unmodeled dynamics. This will involve a parameterization of classes of dynamic controllers obtained by the projective controls technique, and the relating of this parameterization to frequency weightings in a performance index. The parameterization should summarize the design freedom available at a given stage in the design, and provide insight into the available tradeoffs of performance, robustness, and disturbance rejection. Decentralized digital control will continue to be a focus in the problems studied. Some attention will be given to related systems modeling issues, such as choice of input-output pairs for decentralized control and the obtaining of corresponding reduced-order design models. The main challenge in this work will be to formulate in a useful way the controller parameterizations, and to relate these cleverly to corresponding frequency-dependent weights in linear-quadratic optimization problems. An understanding of the fundamental properties of such optimization problems will be a major goal of this research. This should result in a noteworthy increase in our ability to deal realistically with the control of high order lightly damped imperfectly known systems using decentralized measurement and computation, and in the presence of disturbance inputs.

The development of new, physically motivated, parameterizations will be a major research direction in our adaptive control research. The goal here is to attack the design of reduced complexity controllers. Robustness and convergence properties of reduced- complexity adaptive systems are expected to be superior to those attainable with general-purpose parameterizations, such as ARMA-parameterization. Our preliminary results summarized in the proposed research section point in this direction.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] B. D. Riedle and P. V. Kokotovic, "Stability of slow adaptation for non-SPR systems with disturbances," in *Proc. 1986 American Control Conf*, Seattle, WA, June 1986, pp. 97-102. (JSEP/NSF)

[2] H. S. Tharp, J. V. Medanic, and W. R. Perkins, "Robust projective controls for structured perturbations," in *Proc. 1986 American Control Conf.*, Seattle, WA, June 1986, pp. 1833-1838. (JSEP)

[3] P. J. West and W. R. Perkins, "Nash strategies for discrete-time linear systems with multirate controllers," in *Proc. 1986 American Control Conf.*, Seattle, WA, June 1986, pp. 389-394. (JSEP)

[4] B. D. Riedle and P. V. Kokotovic, "Stability bounds for slow adaptation: An integral manifold approach," in *Proc. 2nd Workshop on Adaptive Systems in Control and Signal Processing*, Lund, Sweden, July 1986. (NSF/JSEP)

[5] B. Riedle, L. Praly, and P. Kokotovic, "Examination of the SPR condition in output error parameter estimation," *Automat.*, vol. 22, no. 4, pp. 495-498, 1986. (JSEP/NSF)

[6] P. V. Kokotovic and R. Marino, "On vanishing stability regions in nonlinear systems with high-gain feedback," *IEEE Trans. Automat. Contr.*, vol. AC-31, no. 10, pp. 967-970, Oct. 1986. (JSEP)

[7] B. D. Riedle, S. T. Hung, and P. V. Kokotovic, "From off-line tuning to continuous adaptation of controller parameters," in *Proc. ISA 86 Int. Conf. and Exhibit*, Houston, TX, Oct. 1986. (JSEP)

[8] J. Medanic, H. S. Tharp, and W. R. Perkins, "Selection of the weighting matrices and the degree of relative stability to position spectrum of the optimal regulator," in *Proc. 25th IEEE Conf. on Decision and Contr.*, Athens, Greece, Dec. 1986, pp. 505-508. (JSEP)

[9] B. D. Riedle and P. V. Kokotovic, "Design of a slowly adapting reduced order controller," in *Proc. 25th IEEE Conf. on Decision and Contr.*, Athens, Greece, Dec. 1986, pp. 447-452. (JSEP NSF)

[10] P. Kokotovic, A. Bensoussan, and G. Blankenship, Eds., *Singular Perturbations and Asymptotic Analysis in Control Systems*, Lecture Notes in Control and Information Sciences, Springer-Verlag, 1987. (JSEP)

[11] B. D. O. Anderson and P. V. Kokotovic, "Optimal control problems over large time intervals," to appear in *Automatica*. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[12] P. V. Kokotovic and P. W. Sauer, "Integral manifold as a tool for reduced-order modeling of nonlinear systems: A case study," *1986 IEEE Int. Symp. on Circuits and Syst.*, San Jose, CA, Session WAM3, May 1986. (NSF)

WORK UNIT NUMBER 19

TITLE: Distributed and Decentralized Systems

SENIOR PRINCIPAL INVESTIGATORS:

T. Basar, Research Professor
J. B. Cruz, Jr., Research Professor
P. R. Kumar, Research Associate Professor

SCIENTIFIC PERSONNEL AND TITLES:

R. Bansal, Research Assistant
D. Connors, Research Assistant
J. Perkins, Research Assistant
R. Srikant, Research Assistant

SCIENTIFIC OBJECTIVE:

Attempts to harness several newly emerging technologies, which lead naturally to large scale computer controlled systems, have given rise to a significant interest in the underlying field of distributed and decentralized systems. Most of these systems incorporate task decomposition, multilevel coordination and control, and distributed estimation and computation. Some of them diverge from classical systems in that the basic phenomena governing them are event-driven and discrete. Examples of such event-driven systems are many and include automated VLSI production systems for making printed circuit boards or fabricating wafers in large volumes in flexible electronic assembly systems, communication networks for data transmission, and interconnected computer systems. They require descriptions in terms of discrete quantities such as the number of PC boards to be retested, or other dynamic, logical and linguistic variables, and they operate as event-driven, asynchronous, largely nondeterministic processes, and hence must be analyzed as such. The basic goal in studying such large, complex, and, typically, distributed and decentralized systems is, firstly, to design them for efficiency, and then to control and coordinate them to attain this efficiency. Important issues that arise in the modeling, control, and coordination of such systems are information flow, learning, aggregation, time scale separation, decentralized estimation, and distributed computation. The principal objective of this research unit is to study such issues in order to enhance our understanding of the behavior and control of large scale computer controlled systems in a distributed network, under uncertainty and decentralization.

SUMMARY OF RESEARCH:

During the first phase of this project, one of our focus points has been the derivation of optimum control laws for distributed systems under decentralized nonclassical information. Such systems and the ensuing models arise in practice when the controller memory is limited, requiring each action to depend on the most recent datum. Yet another scenario would be the situation when the physical system is of large size and involves various subsystems which are responsible individually for specific control actions, and there is delay in the transmission of measurement and control information from one subsystem to another. In this context we have shown that a subclass of such problems can be viewed as the transmission of a garbled version of a sequence of Gaussian random variables over a number of noisy channels under a fidelity criterion. Furthermore we have shown that the optimum solution (under a quadratic loss functional) consists of linearly transforming the garbled message to a certain optimum power level and then optimally decoding it by using a linear transformation at the receiving end. We have also extended this result to the case when the communication medium has unknown statistical description and the optimum policies are derived under worst case performance measures involving a variety of fidelity criteria.

We have also addressed some fundamental questions that arise in the control of discrete event systems. One particularly important issue that arises in modern manufacturing systems is the determination of the level at which buffers need to be maintained. We have shown that under some circumstances, a *zero-inventory* policy may indeed be optimal, even in the face of *unreliability*. This is a surprising result since buffers are usually maintained to guard against unreliability. However, there is a deeper phenomenon at work, related to steady state inventory distributions consisting of both probability masses as well as absolutely continuous components, which makes it sometimes optimal *not* to maintain any inventories.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] P. H. McDowell and T. Basar, "Robust controllers for linear stochastic systems with parametric uncertainties," in *Proc. 1986 American Control Conf.*, Seattle, WA, June 1986, pp. 39-44. (JSEP)

[2] S. Li and T. Basar, "Distributed learning schemes for Nash games," in *Proc. IFAC Workshop on Modelling, Decisions and Games with Applications to Social Phenomena*, Beijing, China, Aug. 11-15, 1986, pp. 307-316. (AFOSR, JSEP)

[3] T. U. Basar and T. Basar, "Optimal linear causal coding schemes for stochastic processes in the presence of correlated jamming," in *Proc. 1986 Princeton Conf. on Inform. Sci. and Syst.*, Princeton, NJ, Sept. 1986, pp. 384-386. (JSEP)

[4] V. R. Saksena and T. Basar, "Multimodeling, singular perturbations and stochastic decision problems," in *Advances in Control and Dynamic Systems*, vol. XXIII, C. T. Leondes, Ed. New York: Academic Press, Sept. 1986, pp. 1-58. (JSEP)

[5] R. Bansal and T. Basar, "Solutions to some stochastic team problems and zero-sum games with nonclassical information arising in communication systems," in *1986 IEEE Int. Symp. on Inform. Theory*, Ann Arbor, MI, Oct. 6-9, 1986. (AFOSR, JSEP)

[6] T. Basar and Y. W. Wu, "Solutions to a class of minimax decision problems arising in communication systems," *J. Optimization Theory and Application*, vol. 51, no. 3, pp. 375-404, Dec. 1986. (JSEP)

[7] R. Akella and P. R. Kumar, "Optimal scheduling of a flexible manufacturing system: A stochastic control problem for a system with jump Markov disturbances," in *Computational and Combinatorial Methods in Systems Theory*, C. Byrnes and A. Lindquist, Eds. North Holland, 1986, pp. 131-134. (JSEP, ARO)

[8] P. R. Kumar, "Identification and adaptive control of linear stochastic systems," in *Adaptive and Learning Systems: Theory and Applications*, K. S. Narendra, Ed. New York: Plenum Press, 1986, pp. 87-103. (JSEP, NSF)

[9] P. R. Kumar and P. Varaiya, *Stochastic Systems: Estimation, Identification and Adaptive Control*. New York: Prentice Hall, 1986. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[10] D. H. Cansever and T. Basar, "Sensitivity analysis in multistage dynamic games," in *Optimization Days*, Montreal, Canada, Apr. 30-May 2, 1986. (AFOSR)

[11] U. Shaked and P. R. Kumar, "Minimum variance control of discrete time multivariable ARMAX systems," *SIAM J. on Contr. and Opt.*, vol. 24, no. 3, pp. 396-411, May 1986. (NSF, USARO)

[12] R. Bansal and T. Basar, "Stochastic teams with nonclassical information revisited: When is an affine law optimal?" in *Proc. 1986 American Contr. Conf.*, June 1986, pp. 45-50. (AFOSR)

[13] B. R. Bamieh and T. Basar, "Characterization and uniqueness of equilibria in locational choice problems," in *Proc. IFAC Workshop on Modelling, Decisions and Games with Applications to Social Phenomena*, Beijing, China, Aug. 11-15, 1986, pp. 277-286.

[14] S. Li and T. Basar, "Asymptotic agreement and convergence of asynchronous stochastic algorithms," in *Proc. 25th IEEE Conf. on Decision and Contr.*, Athens, Greece, Dec. 1986, pp. 243-247. (AFOSR)

[15] T. Basar and P. R. Kumar, "On worst case design strategies," in *Proc. Optimization Days 1986*, Montreal, Canada, Apr. 30-May 2, 1986, pp. 64-65. (AFOSR, USARO)

[16] T. Basar and P. R. Kumar, "On worst case design strategies," *Computers and Mathematics with Applications*, vol. 13, nos. 1-3, pp. 239-245, 1987. (AFOSR, USARO)

[17] R. Bansal and T. Basar, "Solutions to a class of linear-quadratic Gaussian (LQG) stochastic team problems with nonclassical information," to appear in *Syst. Contr. Lett.*, May 1987. (AFOSR)

[18] R. Bansal and T. Basar, "Stochastic teams with nonclassical information revisited: When is an affine law optimal?" to appear in *IEEE Trans. Automat. Contr.*, June 1987. (AFOSR)

[19] [illegible] Kumar and [illegible], "Self-tuning trackers," to appear in *SIAM J. Contr. and Optimiz.* (NSF)

[20] S. Li and T. Basar, "Asymptotic agreement and convergence of asynchronous algorithms," to appear in *IEEE Trans. Automat. Contr.*, [illegible] 1987. (AFOSR)

[21] [illegible] and T. Basar, "Distributed algorithms for the computation of noncooperative equilibria," *Automatica*, [illegible] 1987, to appear. (AFOSR)

WORK UNIT NUMBER 20

TITLE: Robust Feedback Control of Nonlinear Systems

SENIOR PRINCIPAL INVESTIGATORS:

J. W. Grizzle, Research Assistant Professor
P. V. Kokotovic, Research Professor
K. Poolla, Research Assistant Professor

SCIENTIFIC PERSONNEL AND TITLES:

K. Beuscher, Research Assistant
R. Gerth, Research Assistant
M. Shor, Research Assistant
T. Ting, Research Assistant

SCIENTIFIC OBJECTIVE:

For physical devices running the gamut from rotating machinery to opto-electronic laser positioning systems, nonlinearities constitute an essential part of any reasonable model. Revolutionary developments in microelectronics, coupled with recent breakthroughs in the understanding of the structural properties of nonlinear dynamic systems, open up new possibilities for the synthesis and implementation of feedback controllers in order to meet the steadily rising needs for high performance and increased efficiency. However, even the most powerful analytical tools that are available today, such as exact linearization via feedback, nonlinear input-output characterizations, and geometric conditions for noninteracting control and disturbance rejection, still require that exact nonlinear models be available. This is in direct conflict with the fact that the mere presence of nonlinearities makes accurate modeling and identification difficult. Consequently, controllers based upon the currently available theory could be highly unreliable.

To remedy this situation, some fundamentally new lines of research are needed for the design of realistic robust controllers for nonlinear systems. Driven by this need, our research program has two key objectives. The first is to develop a fundamentally new *geometric-asymptotic* approach for the synthesis of robust nonlinear controllers; this approach will combine the advantages of exact geometric notions with estimates of sensitivity and robustness obtained from an asymptotic analysis, and will build upon synergisms of two types of expertise available within our research team. The second objective is to deal with circumstances where desired levels of performance *cannot* be achieved by feedback; it is then necessary to restructure the nonlinear systems. Our objective here is to develop a methodology for reconfiguring nonlinear systems for robustness enhancement.

SUMMARY OF RESEARCH:

In the past year, we have made significant inroads in the study of robust feedback control for nonlinear systems. We have, in particular, investigated the important problems of the robustness of such structural properties as right-invertibility, decouplability and feedback linearization with respect to sampling. With current technology, controllers are often implemented digitally and thus these issues are among the most basic that need to be addressed. In this connection we have been able to show that right-invertibility and decouplability are essentially preserved under sampling but that feedback linearizability is usually destroyed by the introduction of the usual sample and hold devices. However, by passing to a multirate sampling scheme, feedback linearizability can be recovered. Moreover, the linearizing feedback can be computed off-line and then implemented as a table-look-up scheme

We have also investigated the effects of possibly nonlinear modeling uncertainty on a variety of control system synthesis problems. In particular, we have addressed the problem of robust stabilization of plant models exhibiting structured uncertainty. We have been able to provide a new algorithm called "Residue Iteration" for designing optimal controllers, which is numerically far more appealing than any existing scheme. A byproduct of this research is a new algorithm for outer-function interpolation that yields much lower order rational interpolants. The significance of this result is that it allows the synthesis of far simpler controllers than any previous technique.

PUBLICATIONS

JSEP-SPONSORED PUBLICATIONS:

[1] P. V. Kokotovic and P. W. Sauer, "Integral manifold as a tool for reduced-order modeling of nonlinear systems: A case study," in *1986 IEEE Int. Symp. on Circuits and Syst.*, San Jose, CA, Session WAM3, May 1986. (JSEP)

[2] P. V. Kokotovic and R. Marino, "On vanishing stability regions in nonlinear systems with high-gain feedback," in *Proc. Seventh Int. Conf. on Analyais and Opt. of Syst.*, Antibes, France, June 1986. (NSF JSEP)

[3] R. Marino and P. V. Kokotovic, "A geometric approach to composite control of two-time-scale systems," in *Proc. 25th IEEE Conf. on Decision and Contr.*, Athens, Greece, Dec. 1986, pp. 1397-1399. (NSF/JSEP)

[4] T. Ting and K. Poolla, "Robust stabilization via nonlinear time-varying feedback," in *Proc. 25th IEEE Conf. on Decision and Contr.*, Athens, Greece, Dec. 1986, pp. 2033-2036. (JSEP)

[5] K. Poolla and T. Ting, "Nonlinear time-varying controllers for robust stabilization," *IEEE Trans. Automat. Contr.*, vol. AC-32, pp. 195-200, Mar. 1987. (JSEP)

[6] P. W. Sauer, S. A. Zaid, and P. V. Kokotovic, "An integral manifold to reduced order dynamic modeling of synchronous machines," *IEEE PAS Winter Meeting*, New Orleans, LA, Paper 87-WM-221-5, Feb. 1987. (JSEP)

[7] P. W. Sauer, S. A. Zaid, and P. V. Kokotovic, "An integral manifold to reduced order dynamic modeling of synchronous machines," *IEEE Trans. Power Syst.*, 1987 (to appear). (JSEP)

[8] M. Spong, K. Khorasani, and P. V. Kokotovic, "An integral manifold approach to the feedback control of flexible joint manipulators," *IEEE J. of Robotics and Automat.*, vol. RA-3, 1987 (to appear). (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[9] J. W. Grizzle, "Feedback linearization of discrete-time systems," in *Proc. Seventh Int. Conf. Analysis and Opt. of Syst.*, Antibes, France, June 1986, pp. 273-281. (NSF)

WORK UNIT NUMBER 21

TITLE: Multiple-Terminal Digital Communication Systems

SENIOR PRINCIPAL INVESTIGATORS:

E. Arikan, Research Assistant Professor
B. Hajek, Research Professor
M. B. Pursley, Research Professor
D. V. Sarwate, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

K. K. Chawla, Research Assistant
M. Chen, Research Assistant
C. D. Frank, Research Assistant
A. Krishna, Research Assistant
U. Madhow, Research Assistant
J. Y. Park, Research Assistant
B. Radosavljevic, Research Assistant
D. J. Taipale, Research Assistant

SCIENTIFIC OBJECTIVES:

Problems involving the interaction of the elements of a multiple-user communication network are among the most important and most challenging problems in electronic communications. The performance of a communication network depends in a very complex way on the routing algorithm, flow control mechanism, acknowledgement procedure, channel access protocol, error-control code, signaling scheme, receiver processing method, and synchronization technique employed in the lower three layers (network layer, data link layer, and physical layer) of the ISO layered model for the network. The objective of our research in multiple-terminal digital communications is to gain a better understanding of the interplay between these elements. Our research will focus on the issues that arise in mobile radio networks, particularly spread-spectrum radio networks, which must operate in hostile environments that include jamming and fading. This imposes additional requirements on the network in terms of robustness and survivability that will be accounted for in our research.

One of the objectives of our research is to develop new signaling methods and receiver processing techniques that will exploit the implicit and explicit redundancy that is present in the signals and messages. Such redundancy exists in the physical layer (diversity transmission, multipath signals, and modulation), the data link layer (error-control coding), and the network layer (redundant packets and messages). We are particularly interested in the efficient use of implicit and explicit diversity in spread-spectrum radio transmissions to improve communication performance under stressed conditions (e.g., jamming or heavy network traffic). Another objective is to develop network protocols that are compatible with and take advantage of the features of spread-spectrum modulation. Of particular interest are algorithms for distributed scheduling of transmissions. A third objective is to examine the synchronization problem for spread-spectrum radios. Efficient network operation requires fast acquisition of the spread-spectrum signals. Moreover, the acquisition and synchronization systems must be able to operate in the presence of multiple transmissions, jamming and fading to be of any use in a military communications network.

SUMMARY OF RESEARCH:

Considerable progress was made on the problem of diversity transmission for channels with fading and burst interference. Burst interference can be either pulsed interference or partial-band interference in a frequency-hop (FH) system. The goal of our research on this topic is to obtain diversity combining methods that perform well even if the exact nature of the interference and fading are not precisely known. In addition, we seek combining techniques that are robust with respect to the received signal power, the interference power, and the thermal noise level.

In [3] we have demonstrated that the ratio statistic provides a good basis for diversity combining. The performance of a ratio-threshold test (RTT) in conjunction with both square-law combining and majority-logic combining is examined. We have shown that the RTT with majority logic combining gives better narrowband interference rejection capability than the RTT with square-law combining for diversity of order three or greater. More generally, we find that the RTT is an effective scheme against partial-band interference and fading, and, when used in conjuction with majority logic combining, it provides good performance over a wide range of channel parameters.

In other research on FH communication in the presence of partial-band interference and fading, we have begun an investigation of the generation and use of side information with Reed-Solomon and errors-and-erasures decoding. Several alternative techniques for obtaining side information are being considered, and research on the reliability of candidate techniques is in progress. Generally, the determination of the reliability of the side information and the effect this reliability has on system performance is considerably more difficulty for channels with jamming and fading than in our previous work on side information for channels with multiple-access interference only. As a result, our early work has concentrated on narrowband interference rejection where some of the concepts developed for multiple-access systems apply to the jamming problem as well.

We have begun an investigation into serial techniques for the coarse acquisition of direct-sequence spread-spectrum signals using pseudo-noise (PN) sequences. The protocol being studied involves correlating the received signal with the local reference signal over a time period (window) which is very short compared to the period of the PN sequence. A three-way decision (Accept, Reject, or Expand Window Size) is then made. An advantage of the scheme is that one can quite quickly decide when the received signal and local reference are not in approximate synchronism. We have used a new bound on the aperiodic autocorrelation of PN sequences in analyzing the performance of such systems. The new bound is much tighter than previously known bounds for sequences of long period. Our results indicate that the average time to achieve coarse synchronization is much smaller than previously determined. However, the differences are most apparent when the PN sequences have very long periods.

We have started an investigation of coding for channels with input constraints, such as dc-free coding for optical channels and magnetic recording subject to run-length constraints. We have developed an encoding-decoding algorithm that can achieve rates up to channel capacity whether the channel is noisy or not. In the noiseless case this algorithm is easily implementable, requiring only low-precision arithmetic and finite memory. This algorithm can also be used for data-translation from one set of constraints into another. Using this algorithm, we have been able to give, in certain special cases, a constructive proof of Orstein's isomorphism theorem, which states that any two Bernoulli shifts with equal entropy are, in a certain sense, equivalent.

We have discovered a polynomial-time algorithm for scheduling transmissions in a spread-spectrum packet radio network to avoid primary collisions of packets. The algorithm produces transmission schedules which maximize the rate that either link or end-to-end demand is satisfied in the network.

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

Chapters in Books

[1] J. C. Kieffer, "Sturmian minimal systems associated with the iterates of certain functions on an interval," to appear in *Springer-Verlag Lecture Notes in Mathematics: Proceedings of the Special Year on Dynamical Systems, University of Maryland, 1986*. (Springer Verlag: New York), 1987. (JSEP/NSF)

Journal Articles

[2] M. B. Pursley, "The role of spread spectrum in packet radio networks," (Invited Paper) *Proc. IEEE*, vol. 75, pp. 116-134, Jan. 1987. (JSEP/ARO/DARPA)

[3] C. M. Keller and M. B. Pursley, "Diversity combining for channels with fading and partial-band interference," *IEEE J. on Selected Areas in Commun.*, vol. SAC-5, pp. 248-260, Feb. 1987. (JSEP)

[4] C. M. Keller and M. B. Pursley, "Clipped diversity combining for channels with partial-band interference--Part I: Clipped linear combining," accepted for publication in the *IEEE Trans. Commun.*, 1987. (JSEP)

[5] J. S. Lehnert and M. B. Pursley, "Multipath diversity reception of spread-spectrum multiple-access communications," accepted for publication in the *IEEE Trans. Commun.*, 1987. (DARPA/JSEP)

[6] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," accepted for publication in the *IEEE Trans. Inform. Theory*, 1987. (JSEP)

Conference Papers

[7] C. M. Keller and M. B. Pursley, "Frequency-hop communications with diversity for channels with fading and partial-band interference," in *IEEE Global Telecommunications Conf. Record*, Houston, TX, Dec. 1-4, 1986, vol. 1, pp. 160-164. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

Journal Articles

[8] M. B. Pursley, "Frequency-hop transmission for satellite packet switching and terrestrial packet radio networks," *IEEE Trans. Inform. Theory*, vol. IT-32, pp. 652-667, Sept. 1986. (ARO)

[9] J. S. Lehnert and M. B. Pursley, "Error probabilities for binary direct-sequence communications with random signature sequences," *IEEE Trans. Commun.*, vol. COM-35, pp. 87-98, Jan. 1987. (ARO/NSFERC)

[10] M. B. Pursley and D. J. Taipale, "Error probabilities for spread-spectrum packet radio with convolutional codes and Viterbi decoding," *IEEE Trans. Commun.*, vol. COM-35, pp. 1-12, Jan. 1987. (ARO/DARPA)

[11] E. Arikan, "An upper bound on the cutoff rate of sequential decoding," accepted for publication in the *IEEE Trans. Inform. Theory*, 1987. (DARPA)

[12] B. Hajek, "Cooling schedules for optimal annealing," accepted for publication in the *Math. Oper. Res.*, 1987. (NSF/ONR)

[13] B. Hajek, "Locating the maximum of a simple random sequence by sequential search," accepted for publication in the *IEEE Trans. Inform. Theory*, 1987. (ONR/ARO)

[14] B. Hajek and T. Berger, "A decomposition theorem for binary Markov random fields," accepted for publication in the *Annals of Probability*, 1987. (NSF)

[15] R. G. Ogier, "Minimum delay routing in continuous-time dynamic networks with piecewise continuous capacities," accepted for publication in *Networks*, 1987. (ONR)

[16] G. Sasaki and B. Hajek, "Optimal dynamic routing by iterative methods," accepted for publication in the *IEEE Trans. Commun.*, 1987. (ONR)

[17] G. Sasaki and B. Hajek, "The time complexity of maximum matching by simulated annealing," accepted for publication in the *J. Assoc. Comput. Mach.*, 1987. (NSF/ARO)

[18] E. Arikan, "Sequential decoding for multiple access channels," accepted for publication in the *IEEE Trans. Inform. Theory*, 1987. (DARPA)

Conference Papers

[19] J. R. McChesney and M. B. Pursley, "Channel access/multiple access performance for SINCGARS packet switched radio network," *Proc. AFCEA-IEEE Tech. Conf. on Tactical Commun.*, Fort Wayne, IN, Apr. 22 - 24, 1986, vol. 1, pp. 7-10.

[20] E. Arikan, "Sequential decoding for multiple access channels," *Abstracts of Papers of the 1986 IEEE Int. Symp. on Inform. Theory*, Ann Arbor, MI, Oct. 5 - Oct. 9, 1986, p. 2. (DARPA)

[21] A. W. Lam and D. V. Sarwate, "Time-hopping and frequency-hopping communications," *Abstracts of Papers for the 1986 IEEE Int. Symp. on Inform. Theory*, Ann Arbor, MI, Oct. 5 - Oct. 9, 1986, p. 142. (ARO)

[22] J. S. Lehnert and M. B. Pursley, "A study of approximations in the analysis of DS/SSMA systems with random signature sequences," *Abstracts of Papers for the 1986 IEEE Int. Symp. on Inform. Theory*, Ann Arbor, MI, Oct. 5 - Oct. 9, 1986, p. 143. (ARO)

[23] M. B. Pursley, "Multiple-access capability of frequency-hop transmission with noisy side information," *Abstracts of Papers for the 1986 IEEE Int. Symp. on Inform. Theory*, Ann Arbor, MI, Oct. 5 - Oct. 9, 1986, pp. 142-143. (ARO)

[24] M. B. Pursley, "Packet error probabilities in frequency-hop radio networks -- Coping with statistical dependence and noisy side information," *IEEE Global Telecommunications Conf. Record*, Houston, TX, Dec. 1-4, 1986, vol. 1, pp. 165-170. (ARO)

[25] A. W. Lam and D. V. Sarwate, "A comparison of two methods for generation of side information in frequency hop spread-spectrum multiaccess communications," to appear in the *Proc. 1987 Conf. on Inform. Sci. Syst.*, The Johns Hopkins University, Baltimore, MD, Mar. 25-27, 1987. (ARO)

[26] S. D. Sandberg and M. B. Pursley, "Simulation of delay in frequency-hop packet radio networks," to appear in the *Proc. 1987 Conf. on Inform. Sci. Syst.*, The Johns Hopkins University, Baltimore, MD, Mar. 25-27, 1987. (ARO)

[27] M. B. Pursley, "Coding and side information for frequency-hop communication in partial-band interference," to appear in *Conference Record, 1987 IEEE Int. Conf. Commun.*, Seattle, WA, June 8-11, 1987. (ARO)

[28] B. Hajek, "Delay and routing in interconnection networks," (Invited Paper) *Flow Control of Congested Networks: Proc. 1986 NATO Conf.*, A. Odoni and G. Szego, Eds. New York: Springer-Verlag, 1987. (NSF AT&T)

[29] B. Hajek, "Four contributions," *Fundamental Problems in Communication and Computation*, T. M. Cover and B. Gopinath, Eds. New York: Springer-Verlag, 1987.

WORK UNIT NUMBER 22

TITLE: Statistical Signal Processing in Communication Systems

SENIOR PRINCIPAL INVESTIGATORS:

A. R. Barron, Research Assistant Professor
H. V. Poor, Research Professor

SCIENTIFIC PERSONNEL AND TITLES:

B. Hagger, Research Assistant
R. Vijayan, Research Assistant
S. Zabin, Research Assistant

SCIENTIFIC OBJECTIVE:

Statistical signal processing functions such as signal detection, estimation, and identification play a key role in the development of effective communications, radar and sonar systems. For example, advanced statistical methods are emerging as being particularly important in digital communications systems operating in channels corrupted by interference from such phenomena as multiple-access noise, intentional jamming, and impulsive noise sources. Conventional demodulation methods, such as coherent matched filtering, often suffer serious performance degradation when subjected to interference of these types; however, this degradation can frequently be eliminated through the use of more sophisticated signal processing techniques.

A central issue in the design of effective signal processing procedures for systems operating in channels such as those noted above is that of channel identification. Although certain aspects of channel identification have been studied extensively, one area in which there is a pressing need for further research is that of identification of impulsive channels. Natural impulsive phenomena are major noise sources in many types of channels including ELF electromagnetic and under-ice acoustic channels. Moreover, man-made impulsive phenomena are a principal background noise source in the environments in which military radio networks must operate. Thus, since it is well-established that impulsive noise can be extremely detrimental to the performance of communications, radar, and sonar systems if not properly suppressed and since impulsive channels often exhibit nonstationary characteristics, the development of effective techniques for identification and tracking of the characteristics of impulsive noise channels is an important problem in the development of systems that can approach the performance limits set by such channels.

The overall objective of this research project is to study the general problems of identification and tracking of impulsive channels. A thorough study of this area is planned, including the development of suitable channel models, the derivation and analysis of optimum batch and recursive nonlinear estimation algorithms for identification/tracking, and the application of these algorithms to develop adaptive techniques for the reception of signals passing through impulsive channels. It is anticipated that the results of this study will find application in a broad class of areas including digital communications, sonar and radar.

SUMMARY OF RESEARCH:

Our research efforts during this reporting period have focused on two principal aspects of the problem of identifying impulsive channels. These are: (1) parameter estimation in canonical statistical physical models for impulsive channels; and (2) probability density estimation for general parametric channel noise models.

Our work in the first of these areas has focused on the Class A Middleton model, which is a physically based model that is known to accurately characterize a wide variety of impulsive phenomena, including under-ice acoustic noise and man-made electromagnetic interference. This model has two basic parameters, A and Γ, which characterize the frequency and severity of the impulses. In this reporting period, we have explored several techniques for estimating these parameters from channel measurements. This work, which is reported in [1], has considered batch algorithms only and thus does not provide methods suitable for real-time processing or for tracking of time-varying channels. We are currently exploring recursive versions of the algorithms studied in [1], and our preliminary simulation analysis has shown promising results for these new algorithms.

In the second of these two areas, we have undertaken a theoretical analysis of the rates of convergence of probability density function estimates for situations in which the density function can be assumed to be a member of a smooth parametric family. These convergence rates lead to performance approximations that are applicable to a wide range of stochastic models including, in particular, impulsive noise models. Our immediate plans in this area include the application of these results to specific parametric models for impulsive channels (such as the Middleton Class A).

PUBLICATIONS AND REFERENCES

JSEP-SPONSORED PUBLICATIONS:

[1] S. Zabin and H. V. Poor, "Parameter estimation in the Middleton class A interference model," *Abstracts of Papers: 1986 IEEE Int. Symp. Inform. Theory*, Ann Arbor, MI, Oct. 1986, p. 28. (JSEP)

[2] H. V. Poor, "Fine quantization in signal detection and estimation," to appear in *IEEE Trans. Inform. Theory*. (JSEP)

PUBLICATIONS UNDER OTHER SPONSORSHIP:

[3] I. F. Blake and H. V. Poor, Eds., *Communications and Networks: A Survey of Recent Advances*. New York: Springer-Verlag, 1986.

[4] H. V. Poor, "Discussion of Influence Functionals for Time Series," *Ann. of Statist.*, vol. 14, no. 3, pp. 829-831, 1986 (invited).

[5] H. V. Poor, "Robustness in signal detection," in *Communications and Networks: A Survey of Recent Advances*, I. F. Blake, and H. V. Poor, Eds. New York: Springer-Verlag, 1986, pp. 131-156. (ONR)

[6] H. V. Poor, "Minimax linear smoothing for capacities: The case of correlated signals and noise," *IEEE Trans. Automat. Contr.*, vol. AC-31, no. 9, pp. 877-878, Sept. 1986. (ONR)

[7] S. Verdú. "Multiple-access channels the point process observations." *IEEE Trans. Inform. Theory*. vol. IT-32. no. 5. pp. 642-651. Sept. 1986. (ARO/ONR)

[8] S. Verdú. "Optimum multiuser asymptotic efficiency." *IEEE Trans. Commun.*. vol. COM-34. no. 9. pp. 890-897. Sept. 1986. (ARO/NSF)

[9] R. J. Barton and H. V. Poor. "A representation of fractional Brownian motion with applications to signal detection." *Abstracts of Papers: 1986 IEEE Int. Symp. Inform. Theory*. Ann Arbor. MI. Oct. 1986. p. 62. (NSF)

[10] A. Barron. "Are Bayes estimates consistent in information?" to appear in *Specific Problems on Communication and Computation*. T. Cover and B. Gopinath. Eds. New York: Springer-Verlag. 1987. (NSF/ONR)

[11] H. V. Poor. Ed.. *Advances in Statistical Signal Processing - Vol. 1: Estimation*. Greenwich. CT: JAI Press. 1987.

[12] H. V. Poor. *An Introduction to Signal Detection and Estimation*. New York: Springer-Verlag. 1987.

[13] H. V. Poor. "Robust filtering." in *Advances in Statistical Signal Processing - Vol. 1: Estimation*. H.V. Poor. Ed. Greenwich. CT: JAI Press: 1987. pp. 329-360. (ONR)

[14] B. Aazhang and H. V. Poor. "Performance of DS/SSMA communications in impulsive channels - Part I: Linear correlation receivers." to appear in *IEEE Trans. Commun.* (ARO).

[15] B. Aazhang and H. V. Poor. "Performance of DS/SSMA communications in impulsive channels - Part II: Hard-limiting correlation receivers." to appear in *IEEE Trans. Commun.* (ARO).

[16] H. V. Poor. "Uncertainty tolerance in underwater acoustic signal processing." to appear in *IEEE J. on Oceanic Eng.* (invited). (ONR)

[17] S. Verdú and H. V. Poor. "Abstract dynamic programming models under commutativity conditions." to appear in *SIAM J. Contr. and Opt.* (NSF/ONR)

WORK UNIT NUMBER 23

TITLE: Basic Research in Electronics

SENIOR PRINCIPAL INVESTIGATOR:

W. K. Jenkins, Research Professor

SCIENTIFIC OBJECTIVE:

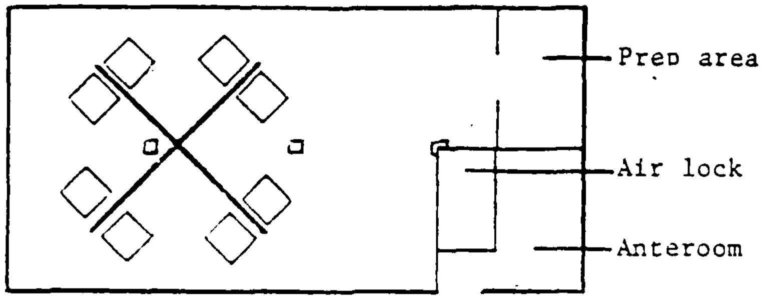
The objective of this research is to tackle fundamental problems of electronic materials, devices and systems in a timely manner and to provide early funding on the start-up of projects which present immediate opportunities of high scientific merit.

SUMMARY OF RESEARCH:

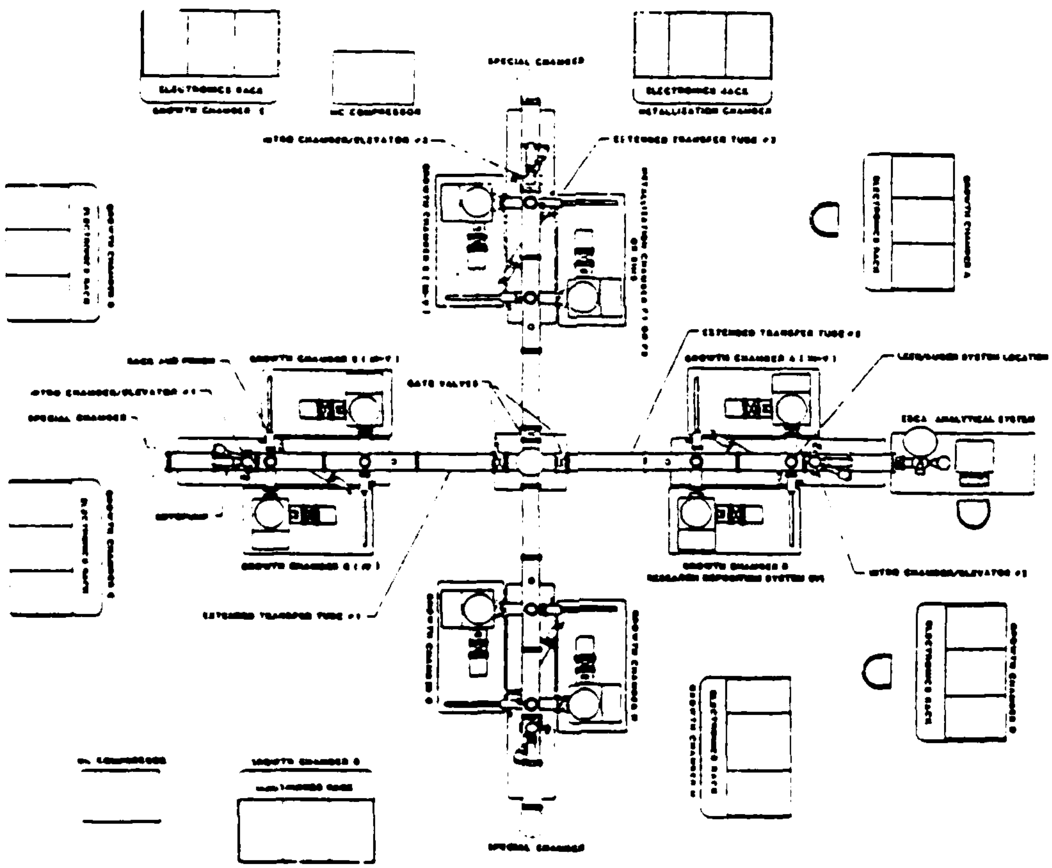
During the last year the current CSL Director (W. K. Jenkins) and the previous CSL Director (T. N. Trick, presently the Head of Electrical and Computer Engineering) have committed a total of $250K of JSEP discretionary funds toward the establishment of an exciting new MBE "Octopus" facility that will be housed in the Coordinated Science Laboratory. The JSEP commitment is in the amount of $100K for the first year, $100K for the second, and $50K for the third year of the current JSEP contract. A team of researchers from the University of Illinois at Urbana-Champaign has designed a unique facility in which state of the art surfaces, interfaces, and multilayers can be synthesized. This new facility will be called the **EpiCenter**, an abbreviation for the U of I CSL-Microelectronics Joint Center for Epitaxial Growth and Surface Science. The $6M initial installation is being established in collaboration with the Coordinated Science Laboratory and the Microelectronics Center on the University of Illinois at Urbana-Champaign campus. As detailed below, funds from a variety of sources have been employed to purchase the equipment now on order.

Seven MBE machines in the EpiCenter will be interconnected by uhv (5×10^{-11} torr) stainless steel transfer lines. From the same vacuum environment, it will also be possible to access advanced instrumentation for surface modification and sample characterization. The crystal growth equipment forms a cross at one end of the 80' x 40' facility. Access to the clean environment of the facility from an observation area is attained through an air lock, as indicated in Figure 1. A sample preparation room providing class 100 clean space in laminar flow hoods is accessible only from the main area. A lounge is provided for planning, discussion, computation, etc. during facility-related activities.

Both the MBE machines and the uhv transfer lines are currently being fabricated by the Perkin Elmer Co. Figure 1b shows the configuration chosen for the system. Machines 1 and 2 on Arm I are III-V compound machines with 2 adapted to gas-source research of Morkoc. Machines 3 and 4 on Arm II are designed for work with metals (3), with both effusion and e-beam sources, and for polar ceramic materials (4). Machine 5 is contributed by the University of Illinois at Urbana-Champaign Engineering Research Center for device work, and the other machine (6) on Arm III is custom designed with e-beam hearths for research into growth of the group IV materials Si, Ge, etc. Finally, machine 7 on Arm IV is specially adopted to Greene's research using ion beam mixing to select particular growth paths of metastable structures. The complex thus contains a wide variety of crystal growth environments that are not ordinarily compatible with one another. Columns III and V elements, for example, are electrically active dopants in group IV semiconductors and must therefore be employed with selective care in group IV synthesis.



(a)



(b)

Fig. [illegible] Schematics showing (a) the EpiCenter facility for epitaxial growth and (b) the approximate layout of the MBE machines.

A special feature of the complex is that the seven machines are interconnected by uhv transfer lines held at a pressure of 5×10^{-11} torr. The purpose is to permit transfer of a given substrate from one growth chamber to a second without surface contamination. This makes it possible to grow on a given fresh substrate an epitaxial layer which is not compatible with the environment needed to grow the substrate. The growth of GaAs on Si is a particular example of an important synthesis problem of this type. The seven machines offer a unique flexibility for research of this type into heteroepitaxy. In particular, the MBE and sample transfer equipment throughout is adapted to 3" wafers so that any sample may receive successive processing in any desired sequence of the seven growth chambers.

A variety of characterization and processing instruments are designed to attach on the ends of the arms. These, also, are fully adapted to the 3" wafer size of the synthesis complex. This permits *in-situ* modification of samples and structure characterization within the common vacuum environment so that surface contamination is avoided. A substrate preparation chamber is attached to the end of Arm I so that substrates can be oxydized, sputtered, annealed, tested, etc. Opposite on the end of Arm III, a rotating anode x-ray source and diffractometer are being set up by Zabel for *in situ* studies of surfaces and multilayers. On Arm IV a PHI XPS unit is being installed for surface studies; its diagnostic capabilities are enhanced by added ion scattering spectroscopy, ultraviolet photoemission, and LEED capabilities. These are in addition to the RHEED and mass spectroscopy diagnostics in each MBE machine. Further, MBE machines 1, 3, and 7 are being specially equipped for ellipsometry, fluorescence, and other optical probes of film growth. Efforts are now being made to obtain Rutherford backscattering equipment for interface and surface studies on Arm IV of the system. A planned future development is the installation of focussed ion beam materials modification and an electron microscope on Arm I. Plans call for the experimental area at the end of Arm IV to become a surface science complex to which freshly grown surfaces from the complex can be transferred.

About \$500K is scheduled from University of Illinois at Urbana-Champaign DOE Program funds for the purchase of the MBE equipment over the years FY 86, 87, and 88. The remaining funds for the \$6M facility have been contributed by NSF Materials Research Laboratory (\$500K), NSF Engineering Research Center (\$200K), JSEP (\$250K), AFOSR (\$600K), and the University of Illinois at Urbana-Champaign, together with a gift from the Perkin Elmer Corporation of approximately \$2.3M.

END
8-87
DTIC